THE CONCEPT, IMPLEMENTATION AND IMPACT OF AN ENVELOPE OROGRAPHY

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1. INTRODUCTION

Mountains exert a considerable influence on the atmosphere over a wide range of space and time scales; from the largest scales, providing a prime forcing mechanism for planetary wave motion in middle latitudes (Held, 1983), to the synoptic scales, playing a crucial role in the triggering of lee cyclones (e.g. Petterssen 1956) and featuring in a number of theories of synoptic scale blocking (e.g. Egger 1978). Below the synoptic scale, the actual weather can also be highly dependent on the nature of the local terrain.

The problems arising in relation to orography in numerical weather prediction can be regarded as falling within three broad categories. The first deals with the best way to represent orographic effects either explicitly or by parameterization. The second concerns the numerical formulations to be chosen so as to minimize problems associated with orography (coordinate, vertical discretization scheme, ...). The third is the interpretation of model output to provide local weather forecasts in mountainous regions. In this paper we shall concentrate on the first topic.

Much of the influence of orography on the synoptic and large scale flow can be achieved in global models by use of what is commonly referred to as "mean" orography. This is essentially an area averaging over model grid squares of a higher resolution representation of the earth's orography, sometimes followed by a further smoothing to reduce numerical problems associated with steep slopes and, in spectral models, by a spectral fit.

It is however, important to include a number of influences of the subgrid scale orographic distribution:

- dynamical low level barrier (blocking) effects.
- influence of unresolved vertically propagating gravity waves on the large scale flow (discussed by Miller and Palmer in this volume).
- enhanced low level dissipation to represent aerodynamic drag over irregular surfaces (as discussed by Mason in this volume).

This paper is mostly concerned with the first point. Intuitively, simple considerations of the energy needed to lift an air parcel over a mountain ridge suggest that the height of the ridge will be a dominant factor in determining whether approaching low level air will rise over the ridge or be decelerated and perhaps diverted sideways. For global models with mesh sizes typically upward of a hundred kilometres, area averaging produces a severe underestimation of characteristic ridge heights for many important mountain ranges. A European example is shown in the upper panel of Fig. 1 which displays the "silhouette" (maximum height) presented to meridional flow by the Alps and the Massif Central as described by a very fine resolution (10' x 10') dataset made available by the US Navy. The smooth curves correspond to "mean" spectral model orographies for horizontal resolutions T63 and T106 used for the experiments described in this paper.

For such narrow mountain ranges there is a clear likelihood that area-averaging will underestimate barrier effects and give excess flow over ridges. This inadequacy has been confirmed by both practical and idealized modelling: Wallace et al. (1983) reported diagnostic studies of operational ECMWF forecasts which showed a close relationship between the location of the largest mean short range forecast errors and the positions of some mountain ranges in the Northern Hemisphere. Moreover they showed the error to be largest where the flow encountered or crossed the mountains. The underestimation of the orographic forcing was proved further by integrations of a barotropic model forced with the short range error diagnosed from the previous set of experiments.

Case studies have shown that simulation of cyclogenesis in the lee of the Alps is generally improved by using some form of enhanced mountains (e.g. Bleck, 1977; Dell'Osso, 1984 and several others). More generally, overall improvements resulting from use of enhanced orography have been found for the extratropics (e.g. Wallace et al., 1983) or for monsoon simulations (Krishnamurti et al., 1984).

Several approaches have been used in practice to enhance the low level barrier effect of mountains. Some correspond to a more or less explicit blocking of the low level flow (e.g. Egger, 1972). Many others correspond essentially to an increase in the height of the mountains used by the models. This approach is supported by some theoretical and idealised modelling studies (e.g. Pierrehumbert, 1984; Pierrehumbert et al., 1985; Cullen et al., 1985) which suggest that in order to represent the barrier effect of mesoscale mountains such as the Alps it is more important to preserve the maximum height of ridges rather than (as does area averaging) the volume of the mountain.

At ECMWF attention has been concentrated on use of so called "envelope" orographies obtained (following a suggestion of J.-F. Geleyn) by adding to the grid square mean orography a multiple of the standard deviation of the subgrid scale orography as computed from the US Navy 10' x 10' dataset.

The lower plot of Fig. 1 shows the Alpine silhouette for envelopes based on use of the factor $\sqrt{2}$ for T63 and T106 spectral resolutions. The height of the barrier is much better captured by the envelope than the mean orography. However, the tendency of area averaging (and spectral fitting) to enhance the width of narrow mountain ranges becomes more pronounced. A clear illustration is provided by Fig. 2 which presents a north-south cross-section of the Alps at close to 10°E. There is an evident risk, in particular at lower resolutions, of a detrimental impact of this spreading of the orography, in particular in situations involving flow parallel to a ridge (or the edge of a plateau).

The original experimentation with envelope orography at ECMWF was carried out by Wallace et al. (1983) using a 2 standard deviation envelope in the former operational 1.875° resolution grid point model. In a trial series of forecast from February 1982, objective verifications showed this envelope produced a

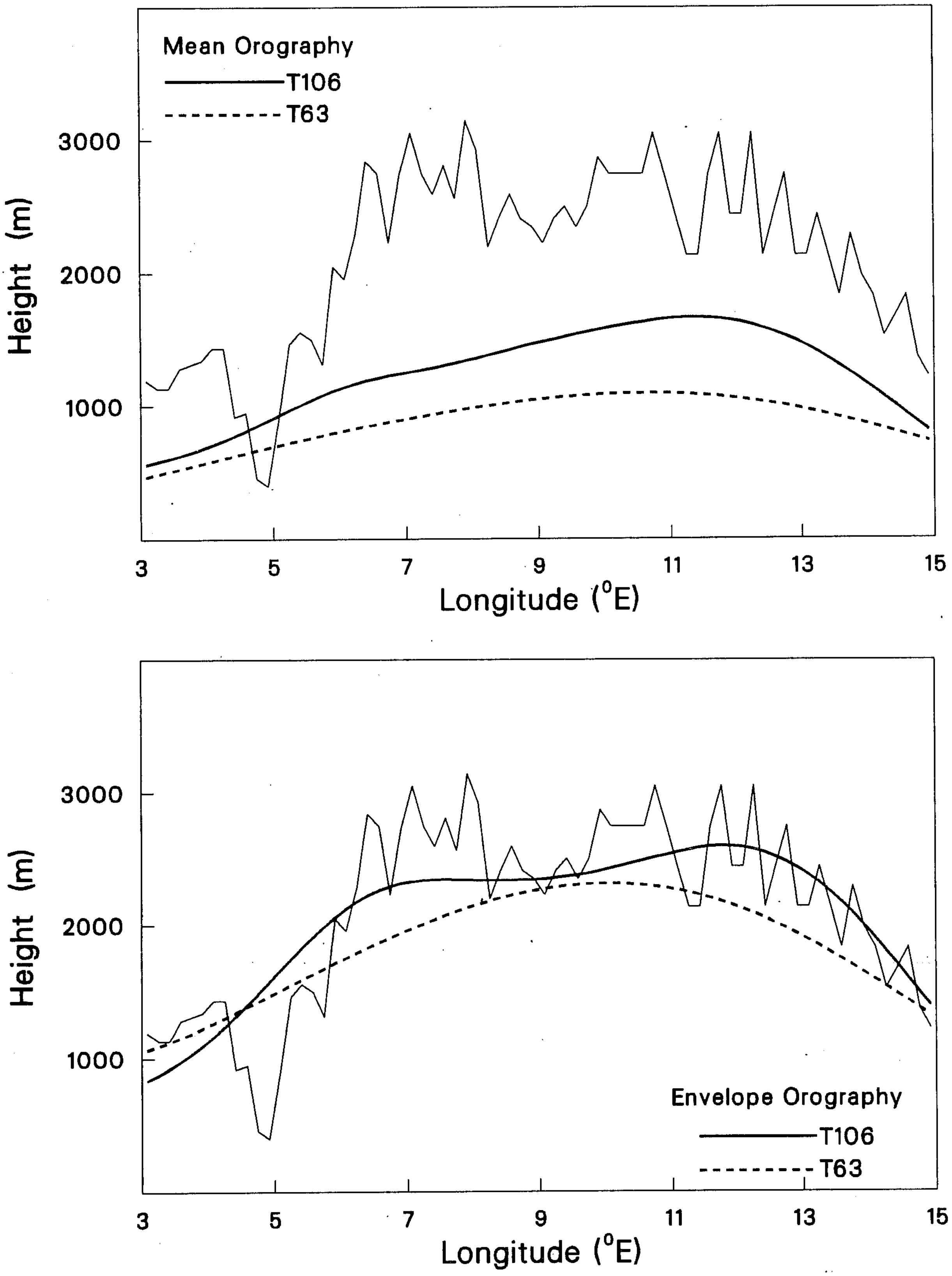


Fig. 1 Silhouette presented to meridional flow by the Southern European orography between 3° and 15°E. Plotted is the maximum orographic height in metres along lines of longitude from 43° to 48°N for
Thin solid lines: Mean orography on 10' x 10' grid
Thick solid lines: Mean (upper) and √2 standard-deviation (√2σ) envelope (lower) orographies of T106 spectral model.
Dashed lines: Corresponding orographies of T63 spectral model.

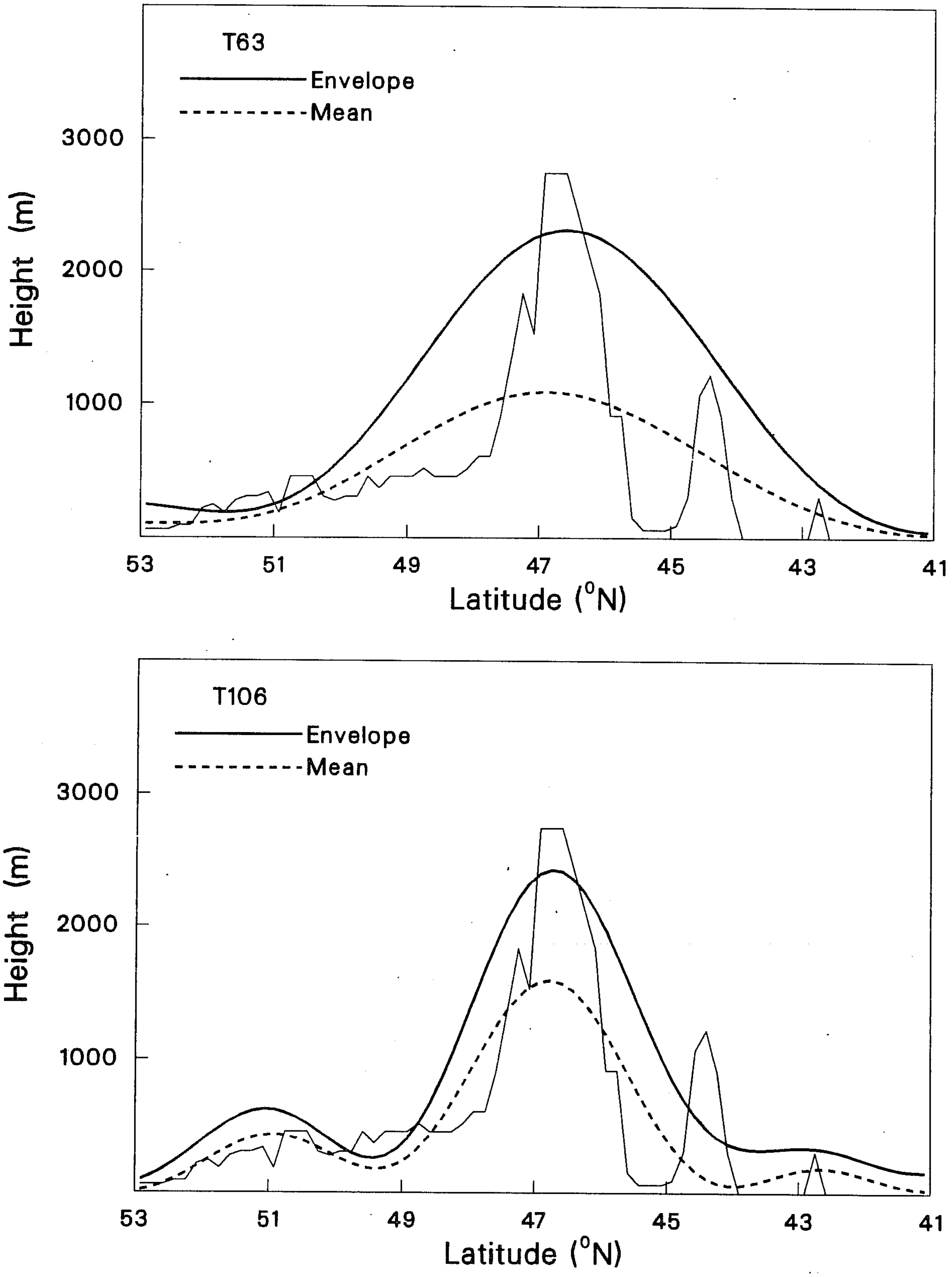


Fig. 2 Meridional cross-section of orographic height in metres from 53°N to 41°N at 10° 5'E showing
Thin solid lines: Mean orography on 10' x 10' grid.
Thick solid lines: $\sqrt{2}\sigma$ envelope orographies of T63 (upper) and T106 (lower) spectral models.
Dashed lines: Mean orographies of T63 (upper) and T106 (lower) models.

net improvement beyond day 4 associated with a modest reduction of time mean error at the end of the forecast range. This was confirmed by further experiments with the grid point model for cases from January 1981 (Tibaldi, 1986), a month for which the then ECMWF operational model had with particularly large systematic errors, and with the spectral model at T63 resolution using a reduced (based on $\sqrt{2}$ standard deviations) envelope (Simmons and Jarraud, 1984).

Despite these encouraging results, a number of detrimental effects were also found when using the envelope. Objective scores indicated a general degradation of short range forecasts in studies with the grid point model, and experiments with the T63 spectral model gave general concern about the behaviour of the envelope in some weather regimes, especially in summer (Simmons and Jarraud, 1984).

In view of these problems and of the obvious sensitivity of the representation of some important mountain ranges to the resolution of the forecast model (as illustrated in Figs. 1 and 2), and bearing in mind the complexity of the earth's terrain and the variability of atmospheric flow, it was decided to reassess the use of an envelope orography as part of a large experimental program to develop a high resolution (T106) operational model. To place results in context and provide evidence to modelling groups employing lower resolution models, comparisons of forecasts using mean and envelope orographies were made also for lower horizontal resolutions.

2. THE EXPERIMENTAL PROGRAMME

In order to have as much confidence as possible in the representativeness of the results, twenty-four cases were selected objectively, choosing initial data for 12Z on the 15th of each month from May 1983 to April 1985. For each case 10-day forecasts were made using a mean and an envelope (based on $\sqrt{2}$ standard deviations) orography with the ECMWF spectral model (Simmons and Jarraud, 1984) at the four resolutions T21, T42, T63 and T106. In addition a set of T106 forecasts was carried out using a lower envelope based on adding one standard deviation to the mean. For each particular initial date the same model options and parameterizations were employed for all resolutions and orographies, apart from use of smaller horizontal diffusion coefficients for T106. For all but the forecasts from the five most recent initial dates, the parameterization schemes were those used operationally with the spectral model up to December 1984 (Tiedtke et al., 1979). The remaining five cases were run using a revised long-wave radiation scheme which became operational in December 1984 (Ritter, 1984) and the revised treatments of clouds, convection and condensation that were implemented operationally with the resolution change in May 1985 (Tiedtke and Slingo, 1985).

Since it would have been impractical to perform data assimilation for all cases, resolutions and orographies, initial conditions in each were case based on the operational T63 analyses. For initial data with T63 mean orography and all T106 datasets, upper-air fields were formed by spectral fits of fields which had been vertically interpolated from one set of coordinate surfaces to the other at each point of the model's Gaussian grid. For T106, mean and envelope orographies were specially created using the higher resolution Gaussian grid, the envelope increment being added only at land points as for T63. Upper air fields, surface pressures and orographies for the T42 and T21 experiments were obtained directly by truncation of T63 fields. A proper land sea mask was constructed for each resolution from the 10' x 10' US Navy data. All other surface fields for all resolutions and orographies were derived by simple linear interpolation from the operational T63 initial conditions.

These procedures, together with the use of the operational T63 analyses for verification, inevitably introduce some bias in favour of T63 with envelope orography, but some evidence has been accumulated indicating that these biases are indeed much smaller than the differences observed. In particular some experiments were performed in which surface fields, such as temperature and snow cover, were initially modified in order to take into account differences in the height of the orography. Subsequent differences in several 10-day forecasts were found to be negligible compared to the ones obtained when comparing mean and envelope orographies. An example will be seen later in Fig.5. Also, the impact of directly computing an envelope orography for T42 rather than deriving it from the T63 version was tested in a situation particularly sensitive to the prescription of orography. The resulting differences after 10 days were again very small.

3. NORTHERN HEMISPHERE RESULTS - OBJECTIVE ASSESSMENT

Most of the objective evaluation discussed in this report is based on anomaly correlations, the correlations between observed and predicted deviations from climatology. This measure was found to give results in reasonable agreement with the synoptic evaluations to be presented in the following section. In most respects similar conclusions were drawn from other scores such as standard deviations.

The 24 cases sampled here were divided into two groups of 12, one broadly representing winter (November to April) and one summer (May to October), the division being based on an EOF diagnosis of the annual cycle (Volmer et al. 1983).

Average differences between 500 mb height anomaly correlations for mean and envelope orographies are presented for each horizontal resolution and season in Fig.3. In winter (left plots) the beneficial overall impact of the envelope is evident for all resolutions other than T21. Up to day 4 there is a gradual change from T21 to T106. There is a strong damaging effect of the envelope at T21, and a very slight worsening at T42. For T63 and T106 there is a clear improvement, this being noticeable earlier in the forecast range for T106. Later in the range, quantitative aspects of the improvement due to the envelope, which is seen at resolutions higher than T21, must be regarded with caution due to sampling uncertainties. For example, the improvement at T63 and T106 from the six cases for winter 1983/84 was substantially larger than from the corresponding cases for 1984/85. It is also worth mentioning that no obvious worsening at short range is observed at T63, in contrast to the earlier experiments which were carried out mostly using the 1.875° grid-point model and a higher envelope based on two standard deviations.

The results for summer, also shown in Fig.3, are in sharp contrast to those for winter. The envelope has a detrimental effect in terms of anomaly correlations across the whole forecast range for T42 and T63. This is noticeable earlier for T42 than for T63. Only for T106 resolution is the performance of the mean and envelope orographies comparable, in an average sense, according to anomaly correlations. It should, however, be noted that at T63 resolution, standard deviations of forecast error do not show a summer bias against the envelope, and for T106 they are lower with envelope than with mean orography, as will be discussed further in Section 5. It can also be seen from Fig.3 that for T106 there is little to choose, overall, between envelopes based on 1 or $\sqrt{2}$ standard deviations.

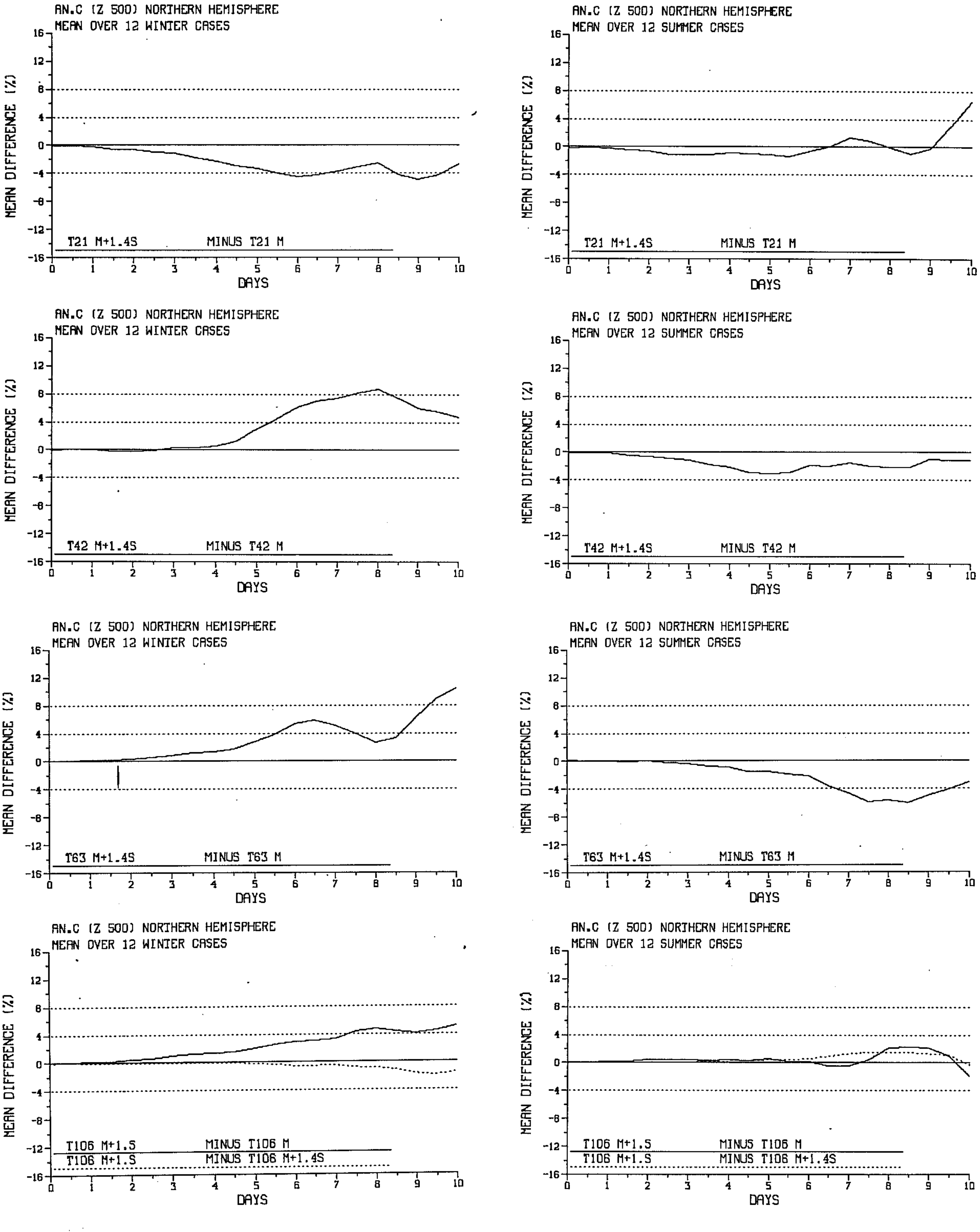


Fig. 3 Mean differences in anomaly correlations of 500 mb height in the extratropical Northern Hemisphere between forecasts using mean and (√2σ) envelope orographies, for T21 to T106 resolutions (top to bottom) averaged over 12 winter (left) and 12 summer (right) cases.

In addition for T106 the dotted line corresponds to the difference between results from the (1σ) and the (√2σ) envelope.

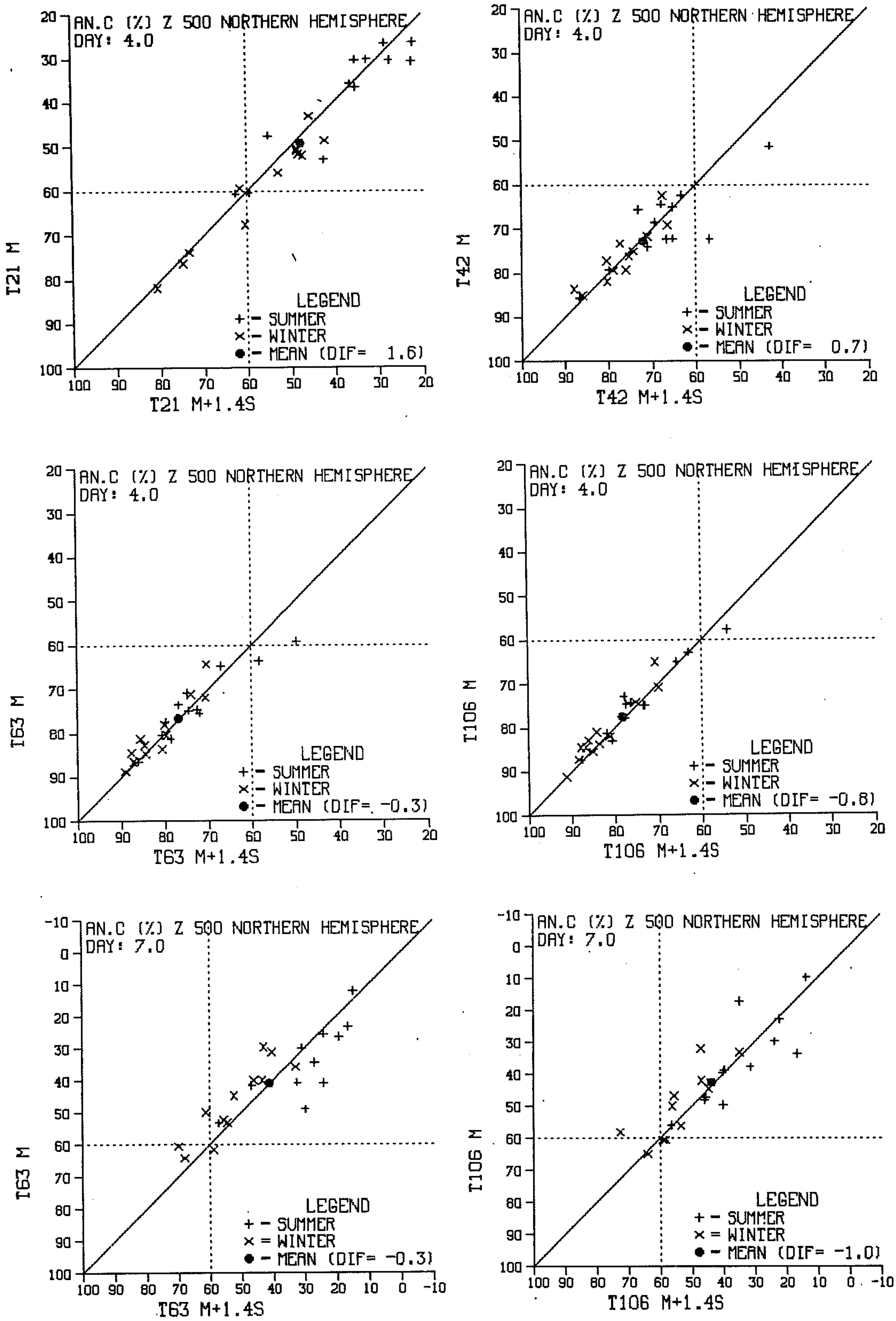


Fig. 4 Upper and middle: Scatter diagrams of anomaly correlations of 500 mb height field in the extratropical Northern Hemisphere comparing mean and ($\sqrt{2}\sigma$) envelope forecasts at T21, T42, T63 and T106 resolution for D+4. Summer cases are represented by + signs, winter cases by x signs, and the mean by a thick dot.

Lower: As above but for D+7 forecasts at T63 and T106 resolutions.

Scatter diagrams showing individual forecast comparisons between mean and ($\sqrt{2}$) envelope orographies for all resolutions for day 4, and for T63 and T106 for day 7, are presented in Fig.4. For T21 there is a considerable dispersion along the diagonal indicating a highly variable forecast quality with particularly poor results in summer cases (denoted by + signs). This may explain why the T21 seasonal behaviour differs from that for the other resolutions, since in summer the other gross errors produced by the very coarse T21 truncation tend to mask rapidly the impact of the envelope.

Accuracy is considerably higher for the other resolutions at day 4 and it can be seen that there is less scatter across the diagonal for T63 than for T42 and less still for T106 indicating (as might be expected) a decrease in sensitivity to the envelope as resolution increases. There is nevertheless a larger mean improvement due to the envelope at T106 because the smaller differences are more systematically in favour of the envelope. Later in the forecast range (lower part of Fig.4) there is more variability and seasonal differences are more clear. The latter is particularly so for T63, with the improvement due to the envelope in winter, and deterioration in summer, occurring in almost all situations.

Examining other levels and variables generally confirms these results. In particular the response observed for the 1000 mb height fields is similar to that already shown for the 500 mb heights, both in summer and winter.

4. NORTHERN HEMISPHERE RESULTS - SYNOPTIC ASSESSMENT

4.1 Introduction

Several studies have emphasized the importance of the Rocky Mountain chain and so further detailed illustrations of similar cases will not be given here. Instead emphasis will be placed on synoptic examples which illustrate some particular aspects of the objective scores and demonstrate how several mountain ranges, other than the Rockies, prove to be important in turn or simultaneously. Also an attempt will be made to relate the way the flow is modified by the change from mean to envelope orography to the arguments presented in the introduction and show how forecast differences tend to originate where a strong flow is incident upon a mountain range. These differences subsequently propagate, mostly downstream, and amplify.

A more complete assessment has been given by Jarraud et al. (1986).

4.2 A European block

The crucial rôle of an envelope in the formation of a European block is shown in Fig.5. This figure displays day-7 T106 forecasts from 15 March 1984, using mean (upper right) and $\sqrt{2}$ envelope (middle left) orographies. Differences are particularly large over Northwest Europe and the North Atlantic, and the structure of the block is well captured with the envelope but not with the mean orography. Fig.5 also shows (lower left) the differences between forecasts using 1 and $\sqrt{2}$ standard deviations; these differences are evidently very much smaller than those between mean and $\sqrt{2}$ envelope forecasts, particularly near the centre of the blocking high. It is clear that in this case the impact of the enhanced orography is far from linearly dependent on the amplitude of the envelope increment.

Examining the difference maps earlier in the forecast range reveals a relatively complex evolution, but it has been possible to demonstrate the particular importance of the North Canadian mountains and Greenland in the establishment of the block. To illustrate this, a series of 5-day mean maps of 500 mb height for the period 20 to 25 March 1984 are presented in Fig.6. As in the instantaneous maps for day 7 shown in the previous figure, the day 5-10 forecast with envelope orography is dramatically superior in its treatment of the block and the ridge downstream over western Siberia.

A number of experiments have been carried out in which the envelope orography has been reduced to the mean in a particular region, and three examples are shown in the remaining panels of Fig.6. Mentioning first an experiment not illustrated, using mean orography over Northern Asia (60°E-190°E; 40°N-80°N) had a noticeable impact only over the North Pacific. Doing the same over the Rocky Mountains (170°W-100°W; 20°N-80°N) led to some modification to the structure of the ridge over the Rockies themselves, and to a slight erroneous deepening of the cut-off south of Iceland, but gave relatively little overall impact, as may be seen from the middle-right map of Fig.6. Conversely, the lower-left map shows how a much more dramatic impact was obtained by using a mean orography over Greenland and Northeast Canada (10°W-100°W; 45°N-90°N). For all features in the Atlantic and Eurasian sectors, the forecast with the composite orography is very much closer to that with the mean orography everywhere than it is to that with the complete envelope. The lower-right panel shows a smaller but still significant influence of the Alps and Pyrenees (10°W-25°E; 35°N-55°N). Using a mean orography over this area degrades the

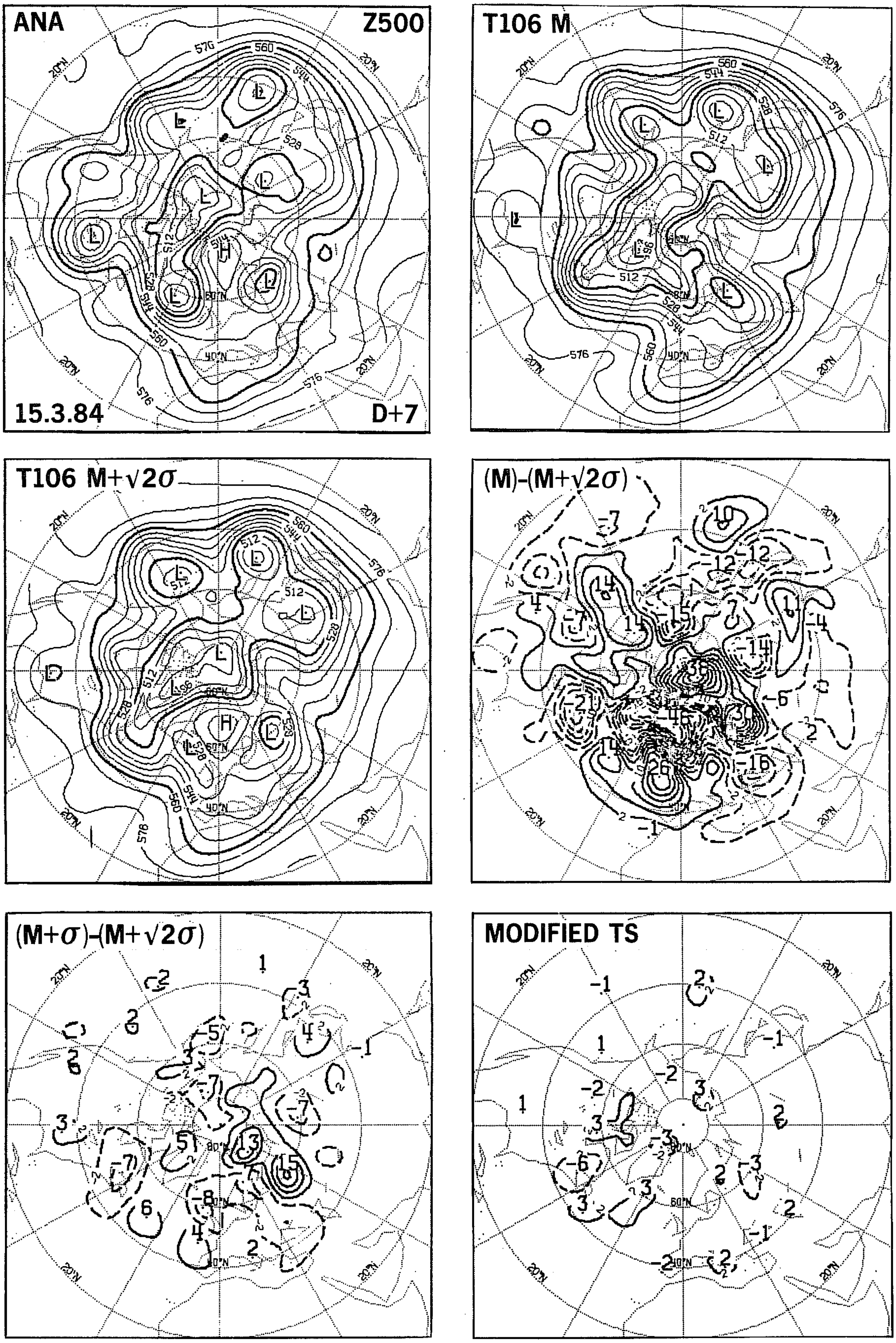


Fig. 5 Analysed 500 mb height field for 22 March 1984 and corresponding D+7 T106 forecasts using mean and (√2σ) envelope orography together with the associated forecast difference maps. In addition are shown differences between (1σ) and (√2σ) envelope but using different surface temperatures (lower right, see text).

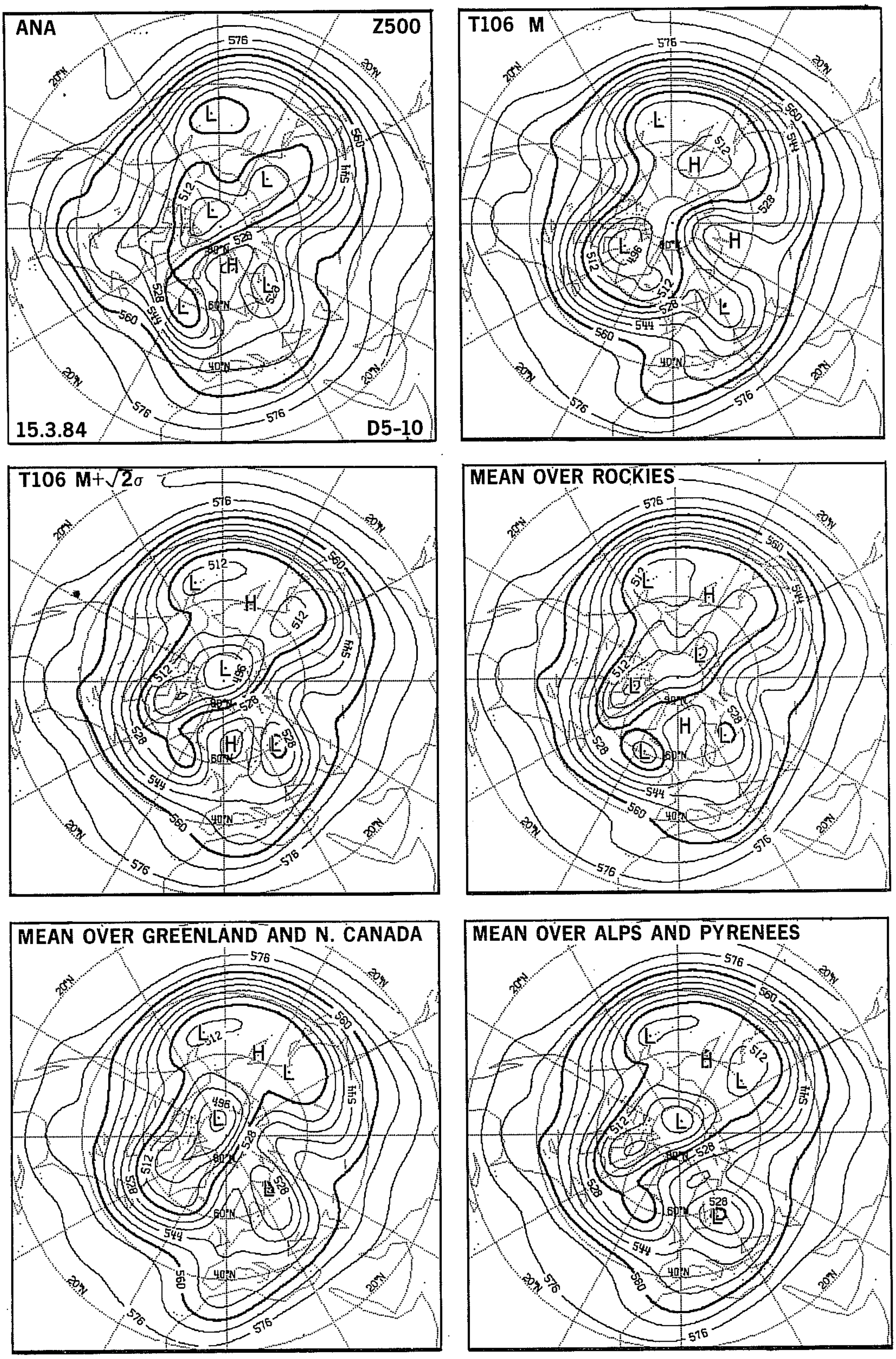


Fig. 6 Mean analyzed 500 mb height field for the period 20-25 March 1984 (upper left) and corresponding day 5-10 T106 forecasts from 15 March using the following orographies

Upper right : Mean
Middle left : Envelope
Middle right: Envelope, but mean over Rockies
Lower left : Envelope, but mean over Greenland and Northern Canada
Lower right : Envelope, but mean over Alps and Pyrenees

5-day average forecast such that the low over Eastern Europe is located slightly more to the south and west, with a weakening of high pressure over the Greenwich meridian and a north-westward tilt of the Siberian ridge. Despite this apparent success for the envelope, it should be noted that the envelope forecast failed to simulate the disappearance of the block over the final two days of the forecast.

Two further experiments were performed for this situation in order to test the impact of the procedures used to create the initial conditions. One was to make a forecast with a mean orography but with the initial surface and deep soil temperatures corrected to compensate for the height differences between the mean and envelope orographies. Another was carried out to test the procedure used to perform the vertical interpolation which consisted of interpolating from the envelope to the mean and back to the envelope, and then running a 10 day forecast. In both cases the impact was found to be negligible. As an example, a difference map showing the impact at day 7 of the change in surface temperature is included in Fig.5 (lower right).

4.3 Mediterranean cyclogenesis

For the European region the importance of enhancing the orographic forcing of the Alps to improve the simulation of Mediterranean cyclogenesis has been stressed by many authors (e.g. Bleck, 1977; Mesinger, 1977; Mesinger and Strickler, 1982; Dell'Osso, 1984). Similar results have been obtained here on the very few cases of our sample when such cyclogenesis occurred.

As an example, Fig.7 shows day-3 forecasts of 500 mb height and 850 mb wind for 18 October, 1983, using mean and $\sqrt{2}$ envelope orographies at T106 resolution. The situation is a classical one for lee cyclogenesis. On 16 October a very intense cyclonic circulation, associated with a deep low centred north of Scotland, prevailed over Western Europe. One day later, the 500 mb trough had deepened and reached Scandinavia; it then extended southward with an indication of a cut-off over the Alps, and with a surface low appearing over the Northern Adriatic. By the 18th, as shown in the upper panels of Fig.7, an intense closed cyclonic circulation was established over Southern Italy with strong northeasterly flow immediately to the south of the Alps.

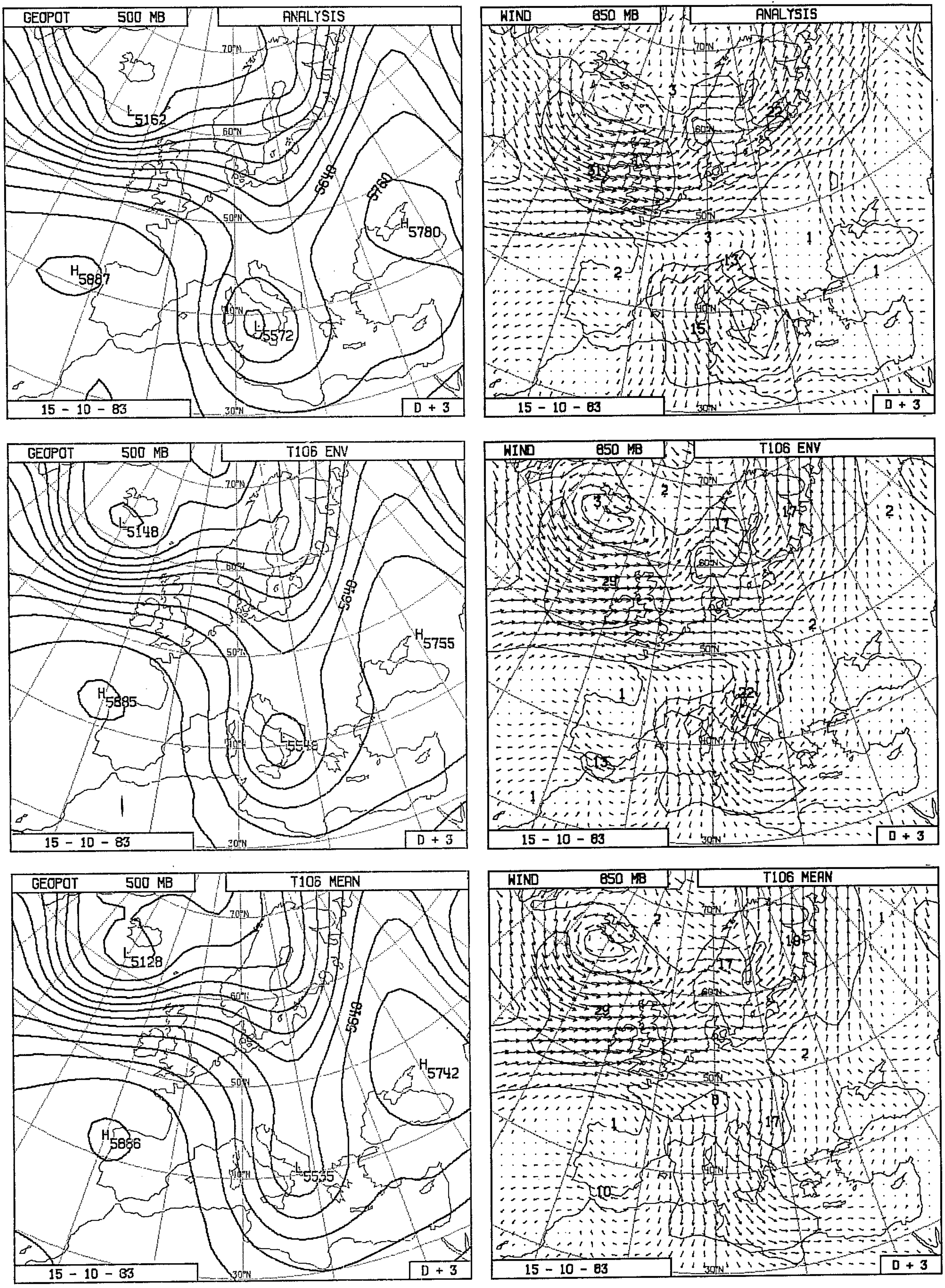


Fig. 7 Analyzed maps showing 500 mb height (upper left, contour interval 60 m) and 850 mb wind (upper right, contour interval 10 m s^{-1}) for 18 October 1983. T106 forecasts from 15 October are also shown, for ($\sqrt{2}\sigma$) envelope orography (middle) and mean orography (lower).

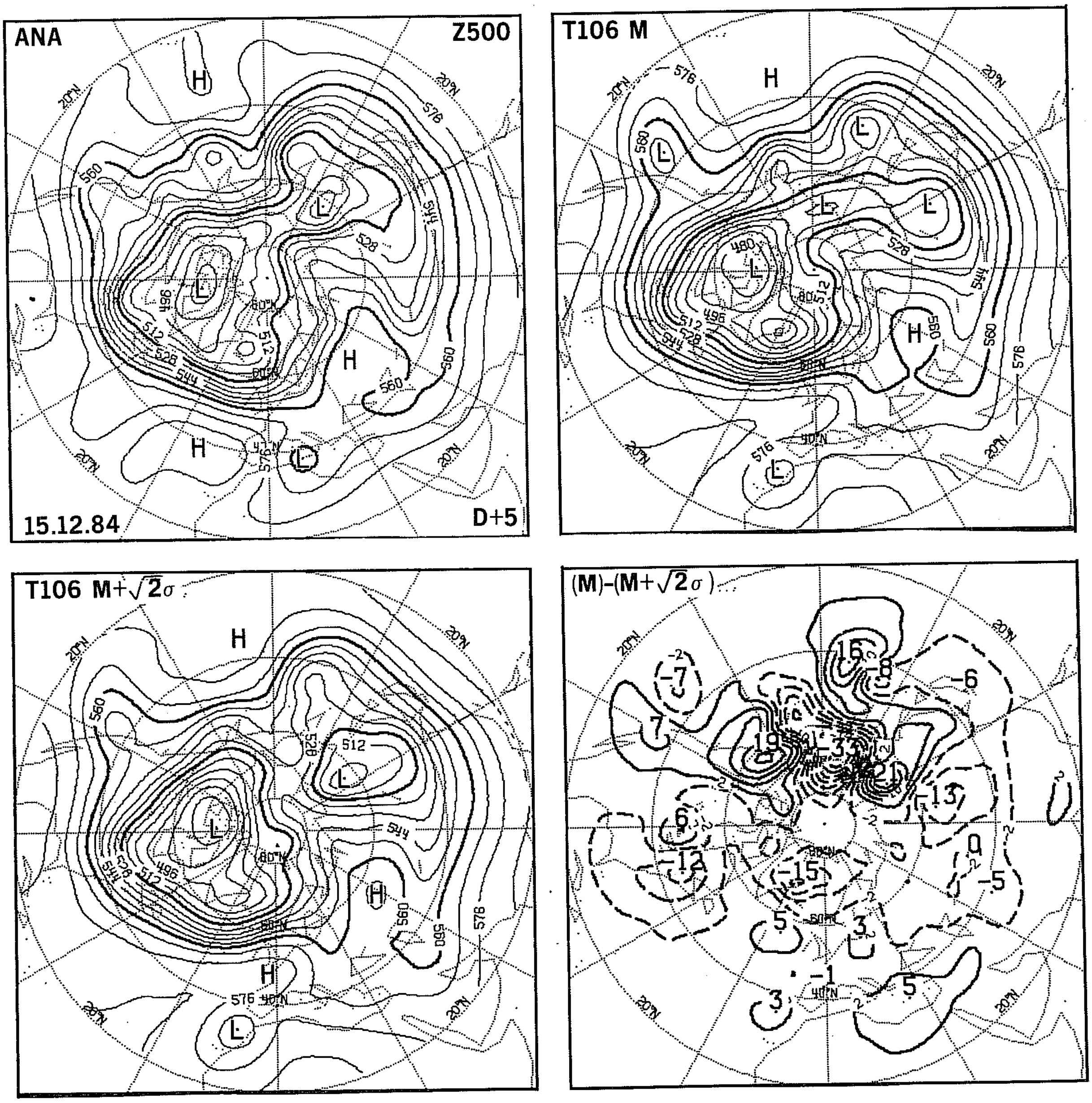
The corresponding day-3 forecast with envelope orography (Fig.7, middle panels) is in many respects satisfactory, although the cut-off low is positioned too far to the east. When using mean orography (lower panels) there is a weaker cyclonic circulation at 850 mb and the low is positioned even further eastward. Examining the 850 mb flow in the vicinity of the Alps suggests that both forecasts underestimate the barrier effect of the Alps, but the forecast using the envelope is clearly closer to reality than that using mean orography in this respect.

4.4 Influence of the Asian mountains, and a low-level barrier effect

The importance of the Tibetan Plateau for the circulation over Asia and the North Pacific has been much discussed. In addition to the Plateau itself, a complex distribution of other significant ranges exists in Central (for example, the Tien-Shan and Altai ranges) and North-east Asia.

An example of sensitivity to these ranges is shown in Fig.8 which displays day-5 forecasts of 500 mb height for 20 December 1984 at T106 resolution using $\sqrt{2}$ envelope and mean orographies. A small cut-off low off the Asian coast is slightly better predicted using mean orography, but almost all other significant differences are in favour of the envelope. In particular the North Pacific ridge is stronger and the Siberian low positioned more to the north. A relationship between these features and the envelope representation of the North and North-east Asian mountains is suggested by examination of the evolution in time (not shown) of differences between the two forecasts, and has been confirmed by an experiment in which the envelope was used everywhere except over this part of Asia.

The northwards displacement of lows over Siberia when using envelope orography, as occurred in the example discussed above, has been found on a number of occasions, and in most cases it results in a better forecast. Such was the case using initial data for 15 October 1983. At this time a low was located north of the Caspian Sea and it subsequently moved very slowly to the east during the 10-day forecast period. That the low was positioned too far to the south when using mean orography was evident already by day 2, and it was thus decided to run two adiabatic forecasts from the same initial date to isolate the mechanical from the thermal forcing. The difference in the position of the low at day 2 can be seen from the upper panels of Fig.9 to be of the order of 3 to 4 degrees of latitude, and appears to be due to a different dynamical adjustment to the height of the orography to the south.


ANA Z500

15.12.84 D+5

T106 M

T106 M+$\sqrt{2}\sigma$

(M)-(M+$\sqrt{2}\sigma$)

Fig. 8 Analyzed 500 mb height field for 20 January 1984, corresponding D+5 T106 forecasts using mean and ($\sqrt{2}\sigma$) envelope orography, and the difference between the two forecasts.

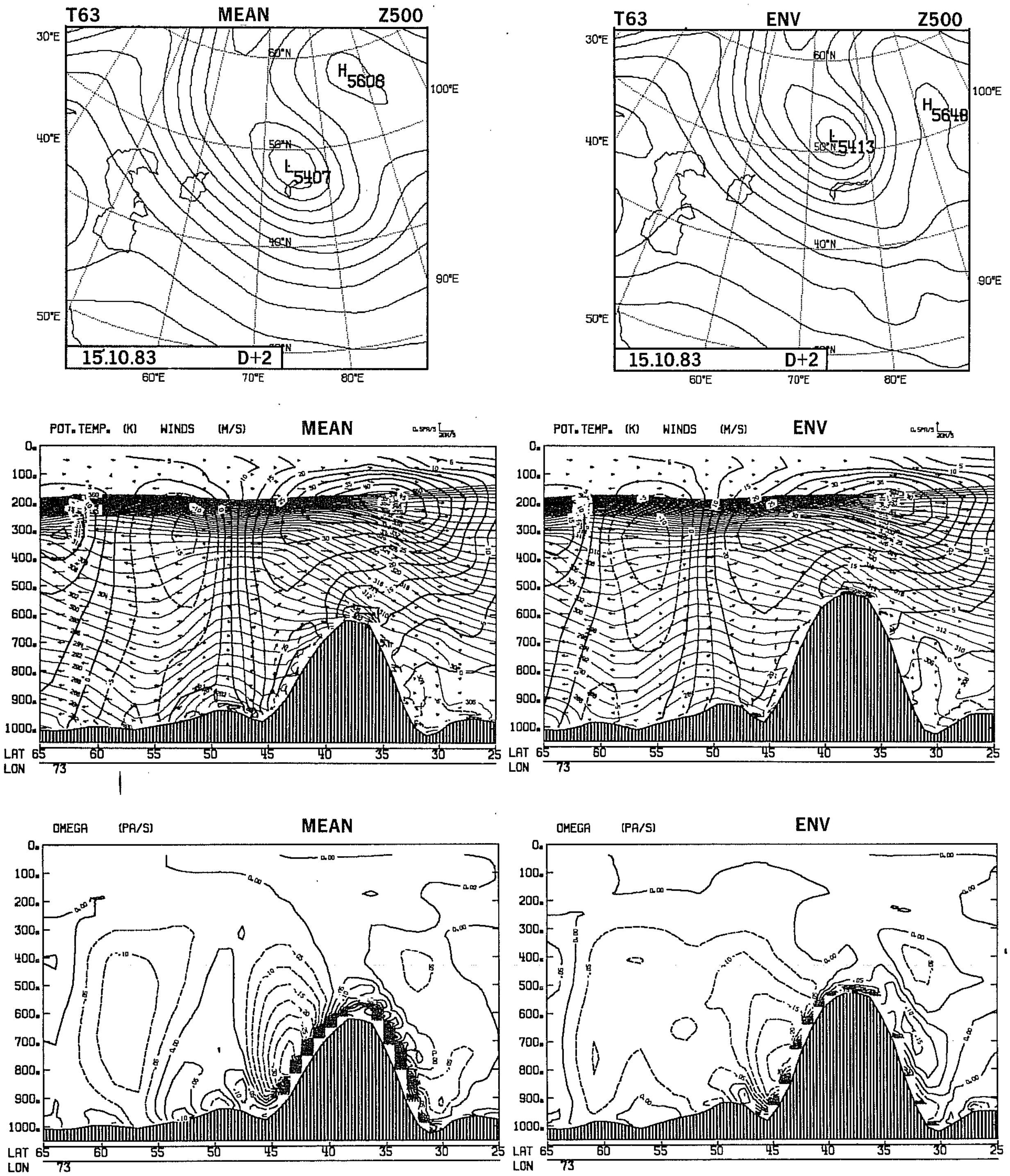


Fig. 9 Two-day adiabatic forecasts for 17 October 1983 using mean (left) and $\sqrt{2}\sigma$ envelope orography (right). The upper plots show 500 mb height fields over western Asia, while the middle and lower plots present cross-sections at 73°E from 65°N to 25°N, for potential temperature and winds (middle), and for vertical velocity alone (lower).

To illustrate this, north-south cross-sections of potential temperature and wind (middle panels) and vertical velocity (lower panels) at 73°E are also shown in Fig.9. With mean orography the potential isotherms tend to follow the northern mountain slope and there is significant rising motion on the upwind side. Isotherms are more normal to the mountain slope for the higher, envelope orography, and the upward motion is reduced. The effect of using the envelope here is to enhance the low-level blocking of the flow which appears to adapt to a new quasi-equilibrium structure with the low located further away from the mountain barrier throughout the troposphere. On some occasions such initially rather small deviations in position can eventually result in much more substantial differences. This occurs when systems reach the Pacific at somewhat different latitudes and then amplify at quite different rates. The latter may result from differences in the temperature of the sea over which the systems pass, although there may also be dynamical consequences of differences in the confluence of polar and subtropical branches of the jet stream in this region.

4.5 Propagation and amplification of differences

The representation of a mountain range such as the Alps has already been shown to be important locally in the examples of cyclogenesis and blocking, but it can also be responsible for significant differences later in the medium range over quite distant places. A striking example, from the 15 February 1985 case, serves to illustrate how differences commonly propagate downstream and amplify where the environment is favourable.

In order to check the impact of the Alps on some features observed over Europe, a T63 10-day forecast was rerun from 15 February 1985 using the envelope orography everywhere except over Western Europe where mean orography was used instead. Fig.10 shows how, as expected, large differences in the early medium range were mainly confined to the region over which the orography was changed. These differences were associated with the position of a cut-off low and decayed together with the cut-off.

However, as seen also in Fig.10, between days 4 and 7 another small area of differences, which had originally propagated northwards, reached the northern branch of the jet, and propagated downstream (with relatively little amplification) following the coast of Siberia. Differences then amplified

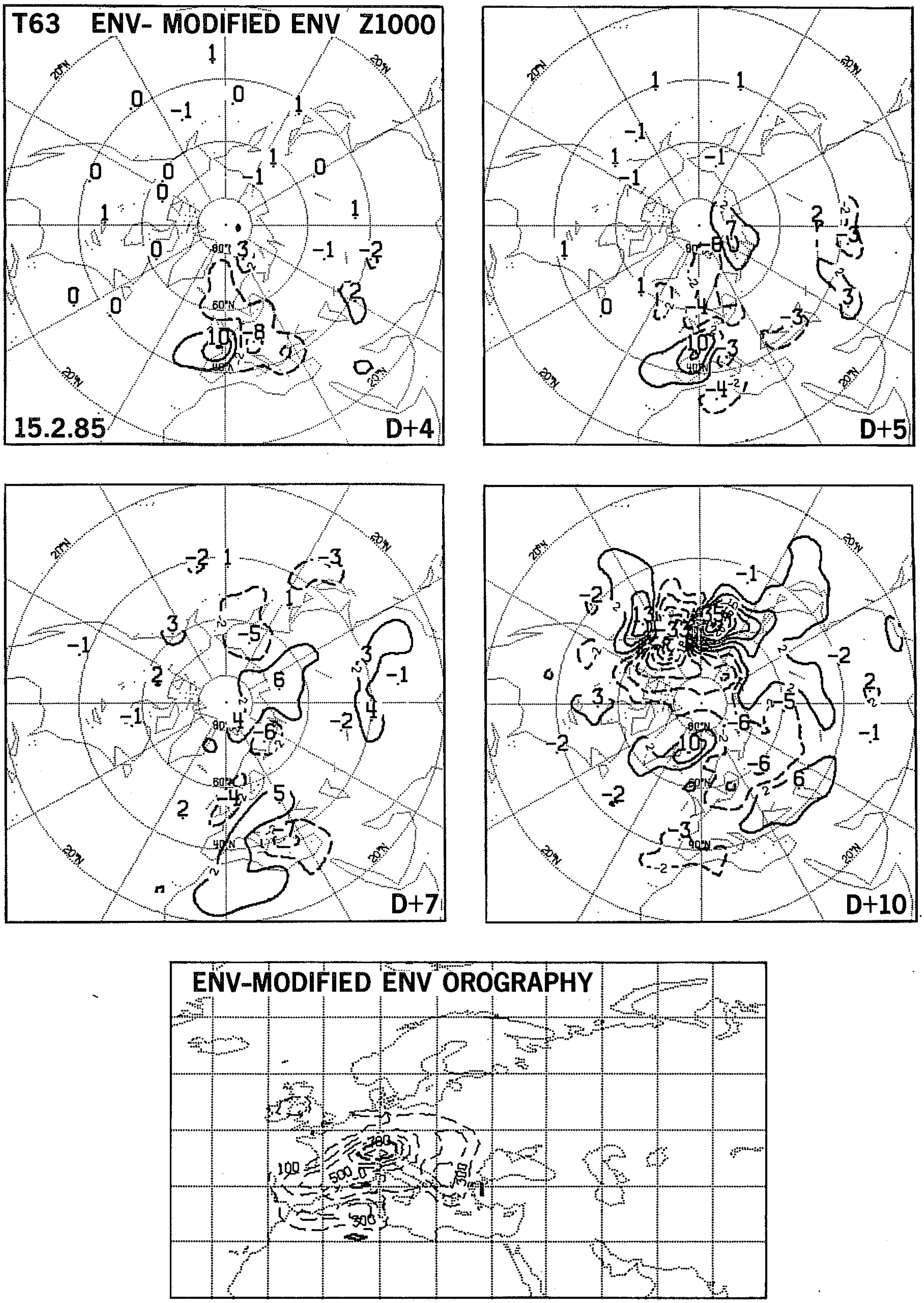


Fig. 10 Forecast-difference maps (in units of dam) of 1000 mb height field for D+4, D+5, D+7 and D+10 T63 forecasts from 15 February 1985. One forecast used the ($\sqrt{2}\sigma$) envelope everywhere, and the other used the same envelope, but reduced to the mean over western Europe. The difference in metres between the two orographies is shown in the lower panel.

rapidly when they reached the North Pacific. By day 10 none of the forecasts is particularly good, but this example demonstrates a sensitivity to remote influences from quite small regions which has to be borne in mind in research aimed at providing reliable forecasts for the later medium range.

From the synoptic assessment of all 24 cases we were unable to identify cases of large amplification of differences associated with upstream propagation. Significant downstream amplification of differences occurred almost systematically in connection with systems which themselves were developing quickly.

4.6 Influence of the envelope over Eastern Asia

Despite the significant overall benefit from using an envelope in winter for the Northern Hemisphere, strong evidence has been found of a detrimental effect in eastern Asia. In particular, anomaly correlations computed for a region including much of China and Japan revealed poorer results with the envelope in winter, the effect decreasing with increasing resolution.

These results are in agreement with limited-area model case studies carried out at ECMWF (Dell'Osso and Chen, 1986). In addition, Sumi and Kanamitsu (1984) noted a tendency of the T42 JMA model, despite using a mean orography, to overestimate airflow round rather than over the Tibetan plateau, in contrast with the situation for the Rockies. This Asian region has also been found (e.g. Chung et al., 1976) to be one of the most active in the Northern Hemisphere for winter cyclogenesis.

Although the degradation of the forecast over the eastern Asian region by use of envelope orography was on average smaller in summer, an example with large differences is shown in Fig.11 which presents day-6 forecasts from 15 June 1984. The forecast with envelope orography exhibits major phase errors with respect to the deep cut-off low off the Asian coast and the trough near 150°W, these errors being substantially less for the mean orography. Here (as in several other cases) differences could be tracked back to the Asian mountains to the north and the east of the Tibetan plateau.

To demonstrate further this point an experiment was run where the envelope was used anywhere except in eastern Asia where the mean was used. The change in

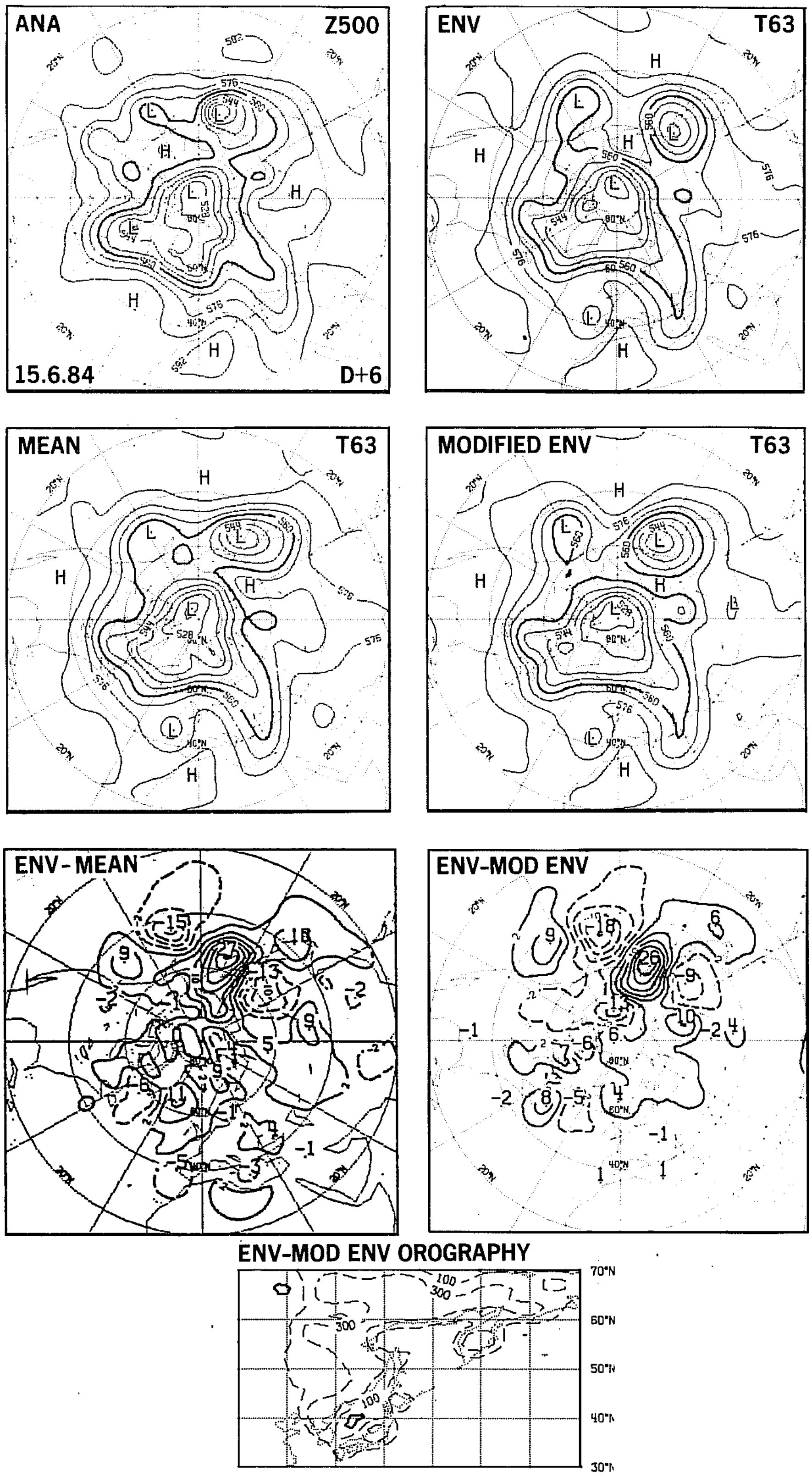


Fig. 11 Analysed 500 mb height field for 21 June 1984 and corresponding T63 D+6 forecasts using (√2σ) envelope (upper right), mean (upper middle left) and a modified envelope orography (upper middle right) where the mean has been used over eastern Asia. The corresponding orography difference (in m) is displayed in the lowest panel.
The figure also displays the corresponding D+6 difference maps (lower middle) between (√2σ) envelope and mean (left) and between (√2σ) envelope and modified envelope (right) orographies.

orography is shown in the lower part of Fig 11. The results, also shown in Fig.11, turned out to be very close to those of the forecast with the mean orography used everywhere. As is often found, mean and envelope produced more similar forecasts at T106 resolution in summer.

4.7 Deterioration at lower resolution due to the envelope in summer

In summer the deterioration observed at T63 resolution due to the use of an envelope appears over several areas. On a number of occasions it is quite large over the North Atlantic and Europe or over the North Pacific and North-east Asia (as illustrated in Fig.11); rarely it is large over North America. This appears to be a consequence of a lesser role of the Rocky Mountains in summer when the main flow is located in a more northerly position.

An interesting point is illustrated in Fig.12 which displays a series of difference maps at day 2 for the forecasts from 15 May 1983. In this case, as in most other cases, the signature of the differences between forecasts using mean and envelope orographies is very similar at all resolutions up to day 2 or 3. Only later do these differences tend to diverge, as differences in synoptic evolution from one resolution to another become significant. It should be noted that for the evaluation of total error, the similar short-range differences have to be considered in conjunction with actual errors (lower part of Fig.12) which are very different for T21 and T106. This is consistent with the deterioration in objective scores seen with the envelope at T21 and the improvement at T106.

One of the critical areas for interaction between the flow and the orography in summer is Greenland and the mountainous islands to the west. In five of the twelve cases, and in others outside this sample, large differences over the North Atlantic, Europe and North Asia appeared to originate from this region, leading in most cases to a degradation of forecasts when using the envelope. An example is shown in Fig.13 which presents day 6 forecasts from 15 May 1984 at T63 resolution. There is a large (although small scale) difference associated with a cut-off low over western Europe. Differences between mean and envelope forecasts at T106 resolution were generally smaller over this area.

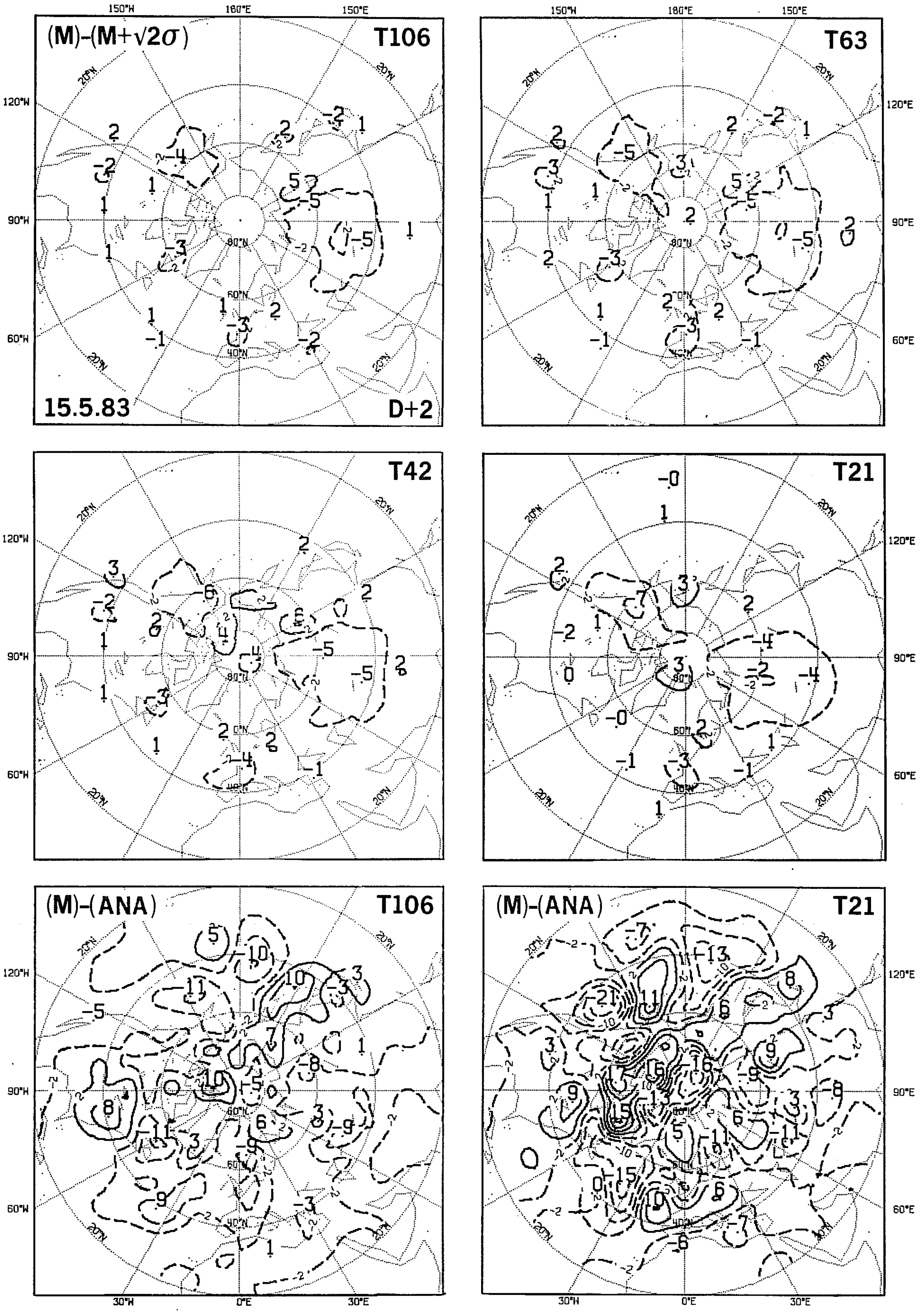


Fig. 12 Difference maps of 500 mb height field for D+2 forecasts from 15 May 1983 by T106 to T21 (upper and middle) using mean and (√2σ) envelope orography. The lower panel shows the corresponding actual errors for T106 (left) and T21 (right) D+2 forecasts using the (√2σ) envelope.

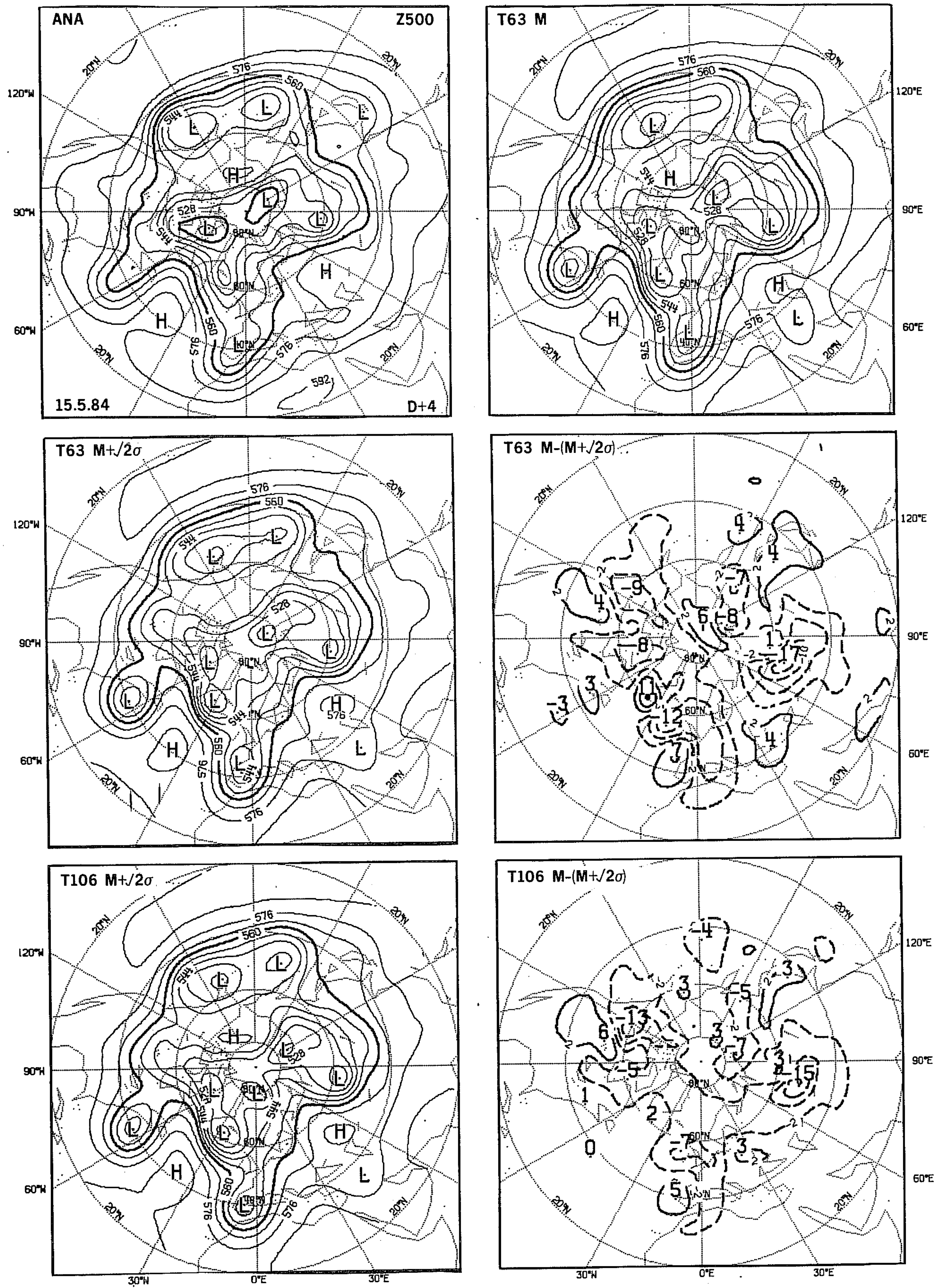


Fig. 13 Upper and middle: Analysed 500 mb height field for 19 May 1984 and corresponding D+4 T63 forecasts using mean and (√2σ) envelope orography together with the associated forecast-difference map. Lower: D+4 T106 forecast using a (√2σ) envelope and corresponding difference map for T106.

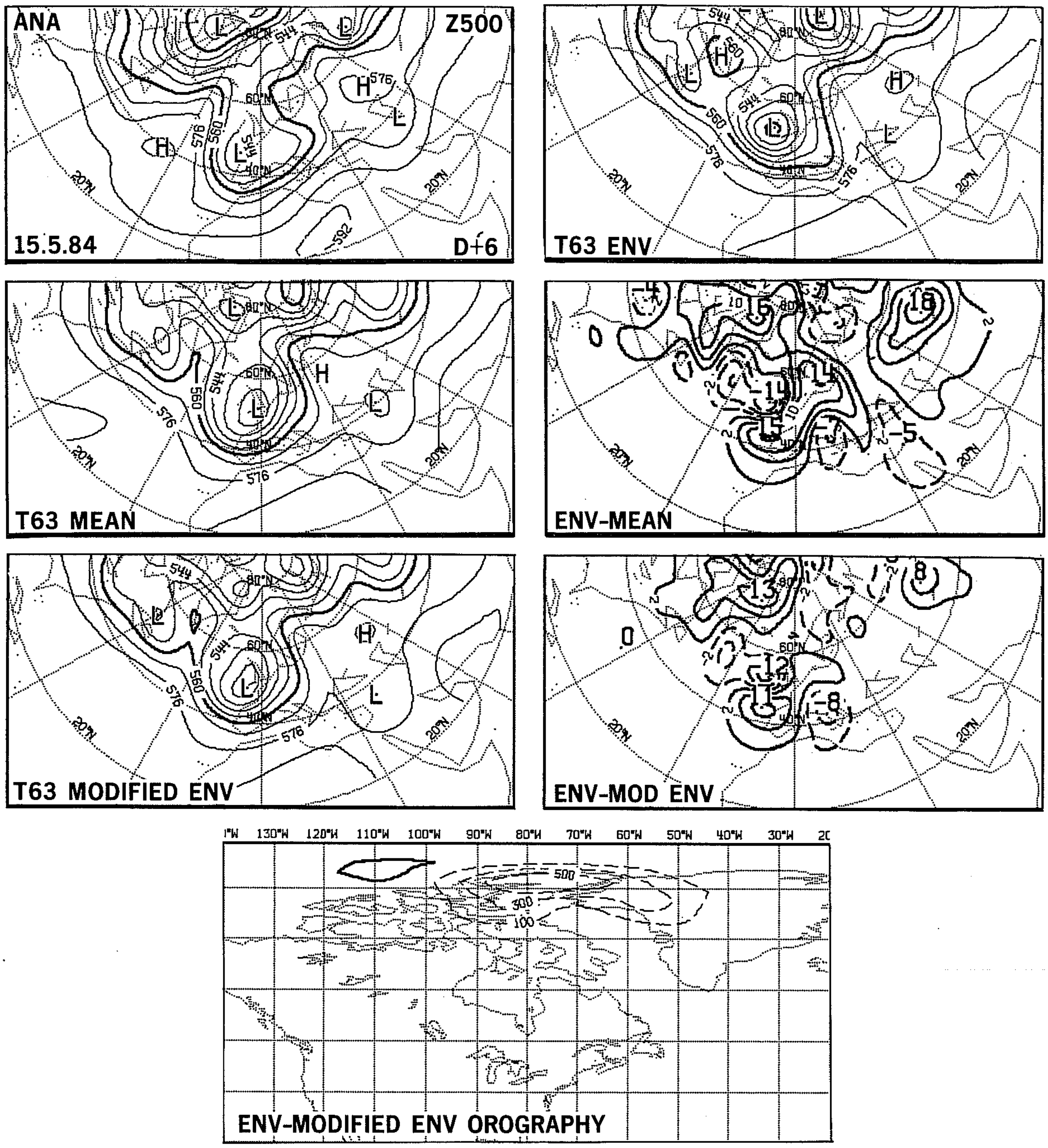


Fig. 14 The analysed 500 mb height field for 21 May 1984 (upper, left) and corresponding D+6 T63 forecasts using $\sqrt{2}\sigma$ envelope orography (upper, right), mean orography (upper middle, right), and a modified envelope orography which is reduced to the mean west of Greenland (lower middle, right). The reduction in orography (in m) is shown in the lowest panel. Differences between envelope and mean forecasts, and between envelope and modified envelope forecasts are also shown (upper middle, right, and lower middle, right, respectively).

Examination of the evolution in time of T63 differences from the start of the forecast suggested a crucial rôle of the mountainous area west of Greenland, and this has been confirmed by an experiment in which the envelope was reduced to the mean over this area. The results at day 6 over the Atlantic and Europe, shown in the upper plots of Fig.14, are much closer to those obtained with the global mean orography than with the envelope, as emphasized by the difference maps. The flow over southern Europe is much better, the small revision to the orography (shown also in Fig.14) being sufficient to remove the erroneous trough over Italy present in the envelope forecast. The Atlantic ridge is closer to reality, and the erroneous anticyclone over the south of Greenland is reduced. The evident importance of the orography west of Greenland in this case suggests that the lesser sensitivity to the envelope at T106 resolution is due to a better definition of the fairly high but isolated mountains of this region. At T63 these appear as a broad mountainous extension of Greenland, particularly in the case of envelope orography.

Although the impact of the envelope orography was generally detrimental at T63 resolution in summer, it should be mentioned that this was far from systematic for all areas and cases.

5. IMPACT ON MEAN (OR SYSTEMATIC) ERRORS

In order to illustrate the relative importance of total errors and of mean errors, Fig.15 shows the root mean square (rms) error for the 500 mb height field computed using the whole ensembles of 12 winter and 12 summer forecasts performed with T106, and the rms error of the corresponding ensemble-mean forecasts for winter and summer. Results are shown for mean and $\sqrt{2}$ standard deviation envelope orographies. Using mean orography, the systematic errors (averaged between day 5 and 10) account for about 14.5% of the total error in winter and slightly more (18.5%) in summer. When using an envelope these figures reduce to about 12.5% in winter and 15% in summer. The winter figures are significantly lower than those (of the order of 25%) obtained by Hollingsworth et al. (1980) using a smaller sample of less independent initial conditions and a much earlier version of the ECMWF forecasting system (including the use of a highly smoothed version of a mean orography).

From Fig.15 it is clear that use of the envelope orography at T106 resolution reduces root mean square errors in both winter and summer. The improvement

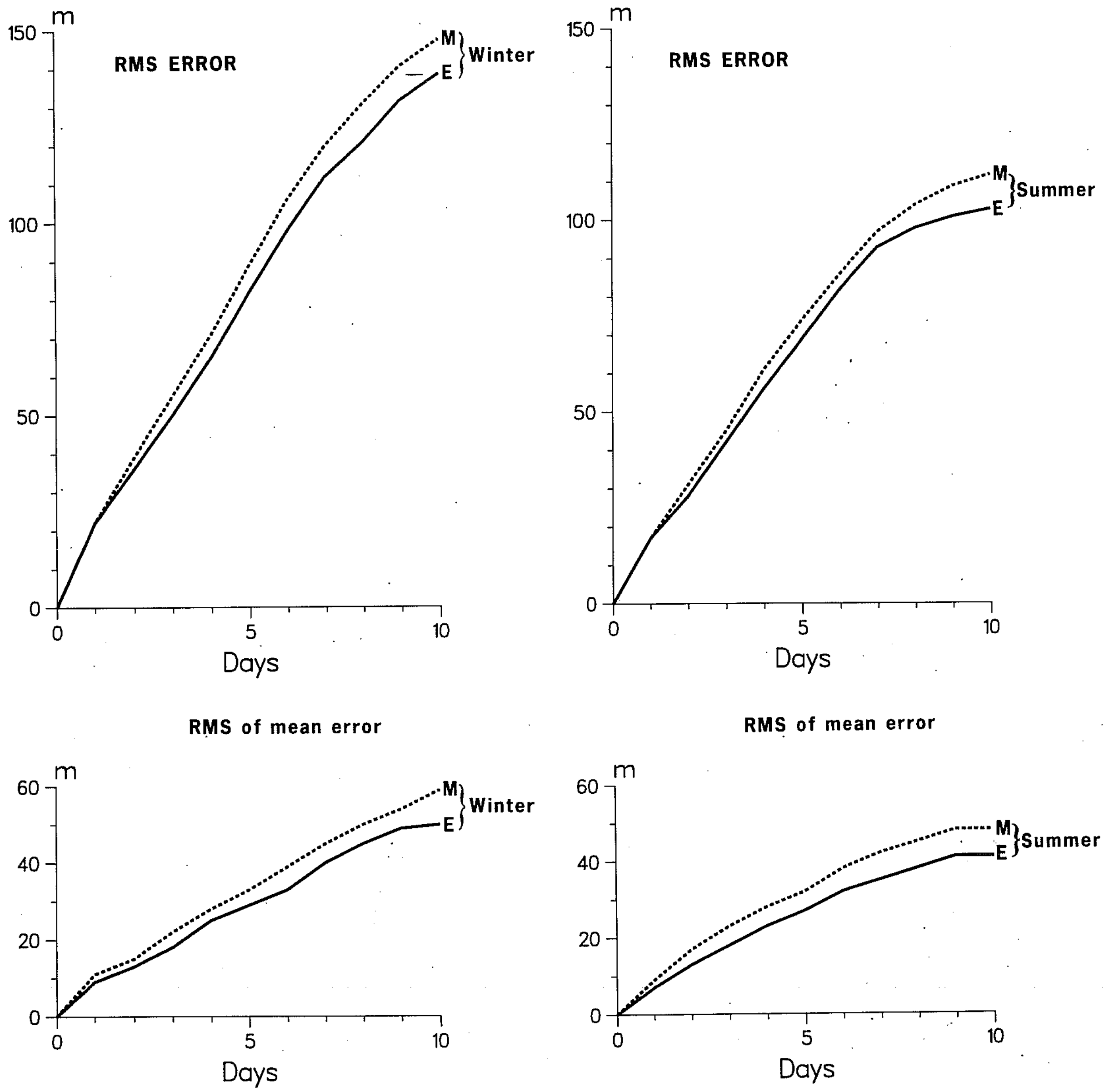


Fig. 15 RMS error of 500 mb height (upper) computed using the ensemble of forecasts in the extratropical Northern Hemisphere by T106 using ($\sqrt{2}\sigma$) envelope (full line) or mean (dashed) orography for the 12 winter cases (left) and the 12 summer cases (right). The lower curves show the RMS errors of the ensemble-mean winter and summer forecasts.

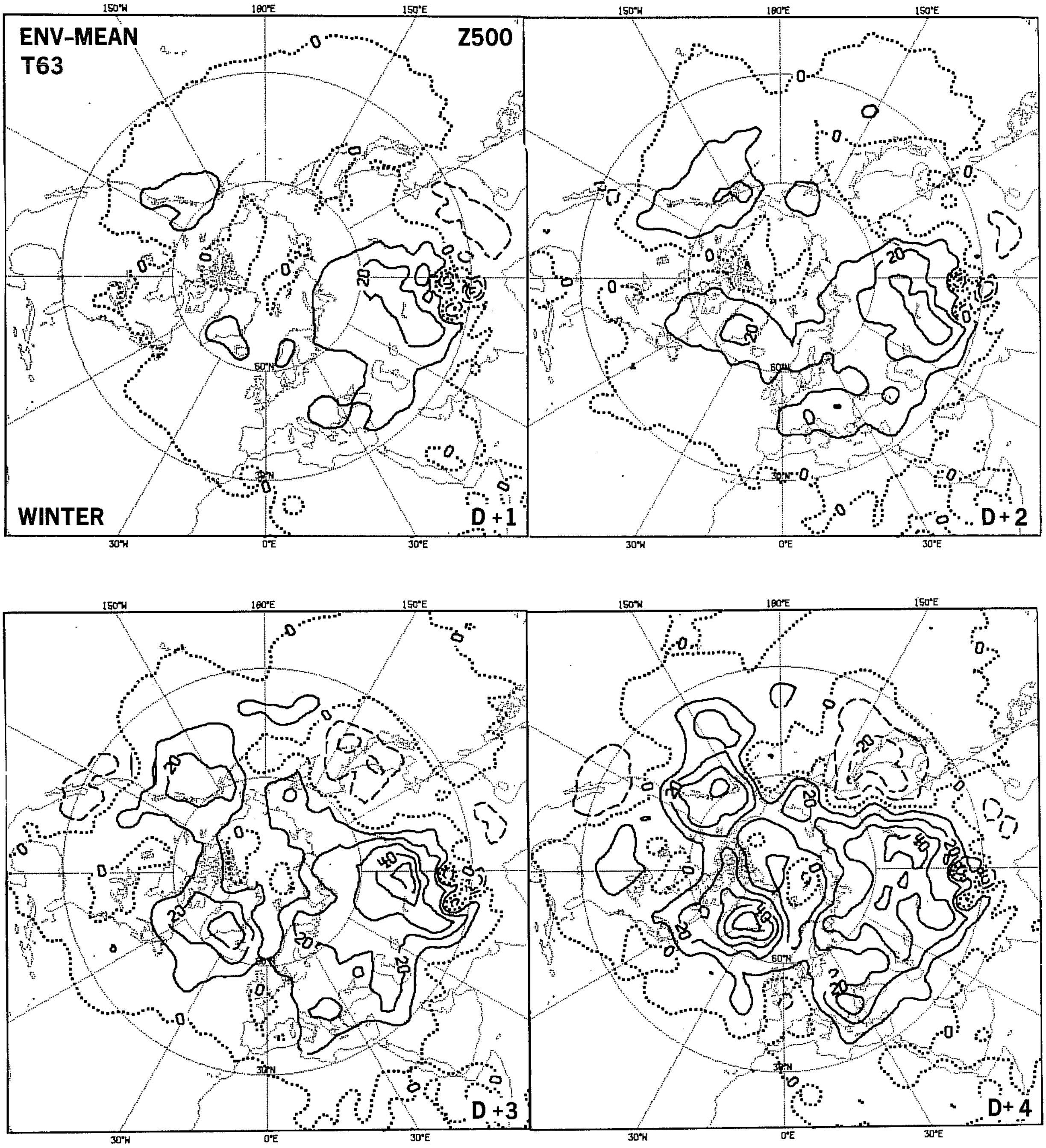


Fig. 16 Average over 12 winter cases of differences between D+1, D+2, D+3 and D+4 500 mb height forecasts by T63 using mean and ($\sqrt{2}\sigma$) envelope orography.

does not apply solely to the systematic (ensemble mean) error. It should be recalled (see Section 3) that there was on average no improvement shown in summer when T106 forecasts were judged in terms of anomaly correlations. Moreover, the T63 forecasts exhibited a summertime deterioration due to the envelope in the comparison of anomaly correlations. Performing calculations similar to those shown in Fig.15 indicates that envelope and mean orographies give summer forecasts of similar overall accuracy for T63 when measured in terms of the root mean square error of the ensemble. A similar conclusion arises from examining the standard-deviation scores of individual cases.

The evolution of ensemble-average differences between envelope- and mean-orography forecasts during the first 4 days of the 10-day range is shown in Fig.16 for the 500 mb height field averaged over the winter cases and T63 resolution. As early as day 1 there is a significant planetary scale component arising as the average of local differences directly related to the Rocky Mountains, Greenland and mountains of Southern Europe and Asia. Up to about day 5 these differences grow largely in place although some spreading can be noticed.

The associated average errors for day 1 and 2 are shown in Fig.17 for the mean and envelope orographies at T63 resolution; it appears that in contrast to the results of Wallace et al. (1983) there is a significant reduction of the short range systematic errors almost everywhere, an exception being the vicinity of Greenland. This reduction is larger than is thought likely (on the basis of limited data assimilation tests) to be due to analysis biases in favour of the envelope orography. As found by Wallace et al., the large error in the low mid-latitude Pacific is not affected by the change in the orography.

In the second half of the forecast range the centres of difference between mean and envelope forecasts tend to drift eastward and follow a similar drift of the systematic errors themselves (shown in Fig.18); this suggests that some planetary scale adjustment might be taking place. As in previous studies, the envelope by then has contributed to reduce significantly the mean errors near the Rocky mountains and over the North Atlantic and Europe. There is however a slight increase over North America and a more considerable one over eastern Asia. The latter is in accord with the previously discussed results of synoptic assessment of individual forecasts for this region.

As mentioned in the synoptic evaluation, the differences between forecasts using envelope and mean orographies are smaller at T106 than at T63. This is clearly seen in the mean differences in winter shown in the upper panels of Fig.19. It is also seen for the summer cases (Fig.19, lower panels). Another striking feature of Fig.19 is the similarity between the average response to the change in orography in summer and winter. The amplitude is slightly weaker in summer, and the difference centres located at low mid-latitudes, for example those over California and the north west Pacific, tend to be reduced or even to disappear, reflecting the northward displacement of the dynamically active part of the flow in summer.

Examining the kinetic energy of the ensemble- and time-averaged flow confirms the finding of previous studies that the kinetic energy of the quasi-stationary waves is improved by the use of envelope orography. The upper panels of Fig.20 show how, for the ensemble-mean T63 fields averaged from days 8 to 10, the level of eddy kinetic energy is increased for almost all zonal wavenumbers at 850 mb and 200 mb, although both sets of forecasts at 200 mb exhibit a much more rapid decay with increasing wavenumber than do the corresponding analyses. Generally similar results are found for other resolutions, and when the calculation is restricted to middle latitudes. For the longer waves, the kinetic energy spectrum is dominated by the contribution from the zonal component of the wind; the separate contributions from the two components at 850 mb are shown in the lower panels of Fig.20.

An exception to the general improvement of kinetic energy levels occurs for zonal wavenumber 2 at 850 mb. The increase of kinetic energy due to use of envelope orography results in poorer agreement with reality, and is in contrast to the results of experiments reported by Tibaldi (1986) using a set of daily cases from January 1981, a month of pronounced mean forecast error. Tibaldi found that the envelope orography gave rise to a reduction in wavenumber 2 (and a more realistic spectrum), and suggested that a Rossby wave resonance mechanism could be responsible for the action of the envelope on the planetary scales, at least for the month in question. Here we have used fewer cases, but drawn from a wider seasonal range, and a wider range of synoptic situations.

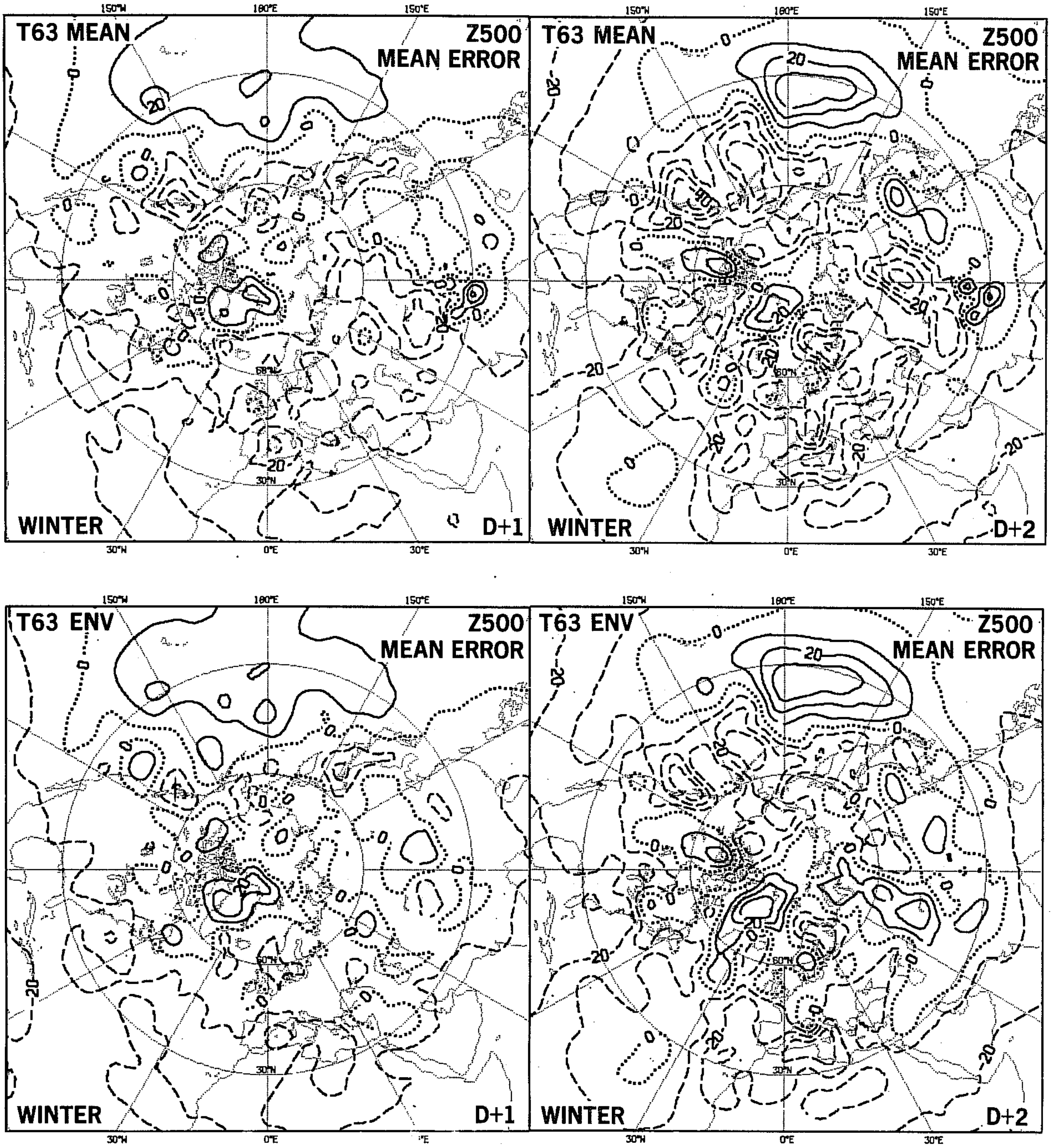


Fig. 17 Average over 12 winter cases of the D+1 and D+2 500 mb height forecast errors by T63 using mean (upper) and ($\sqrt{2}\sigma$) envelope (lower) orography.

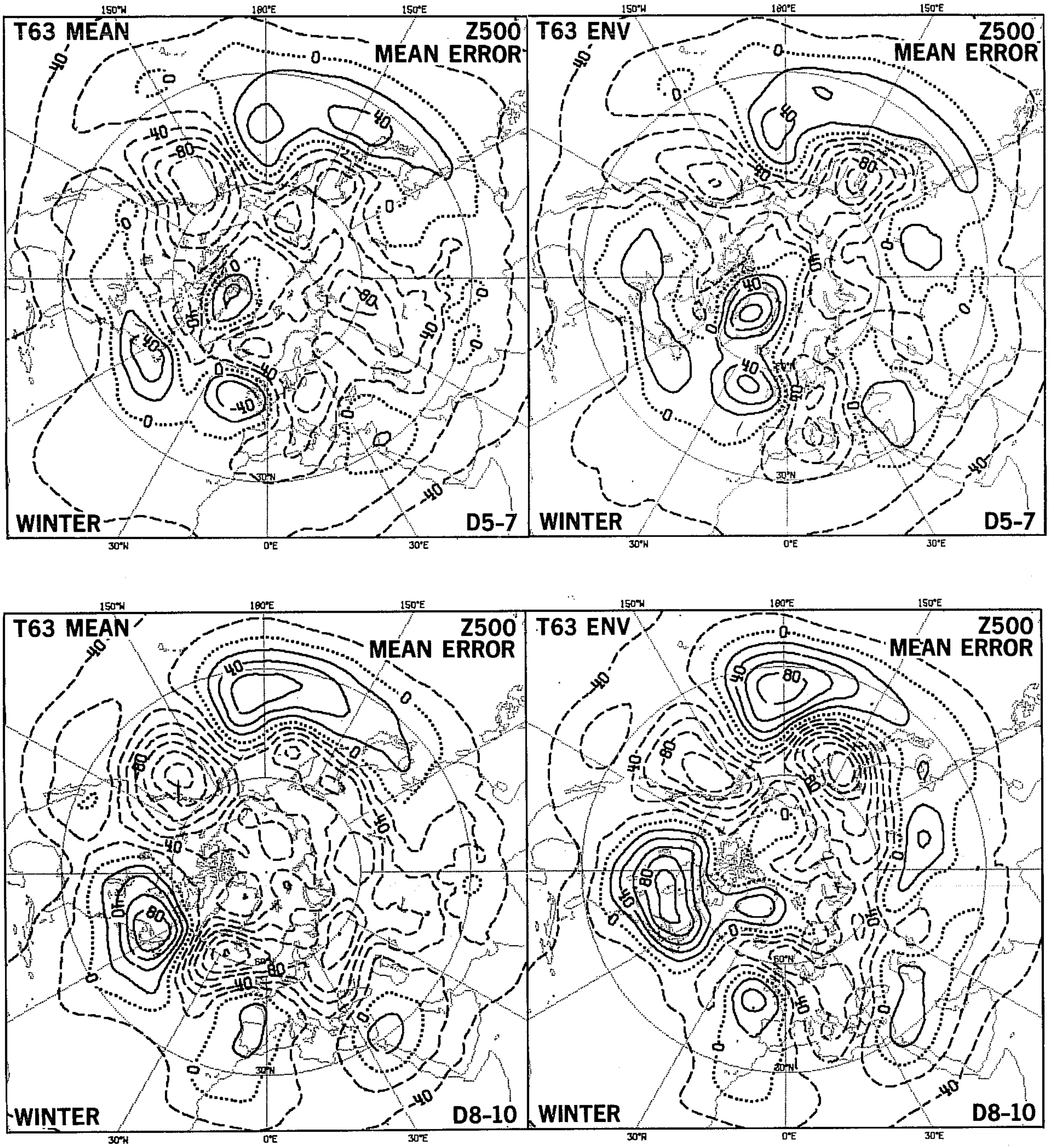


Fig. 18 As Fig. 17, but for D5-7 (upper) and D8-10 (lower) average forecast errors by T63 using mean (left) and ($\sqrt{2}\sigma$) envelope (lower).

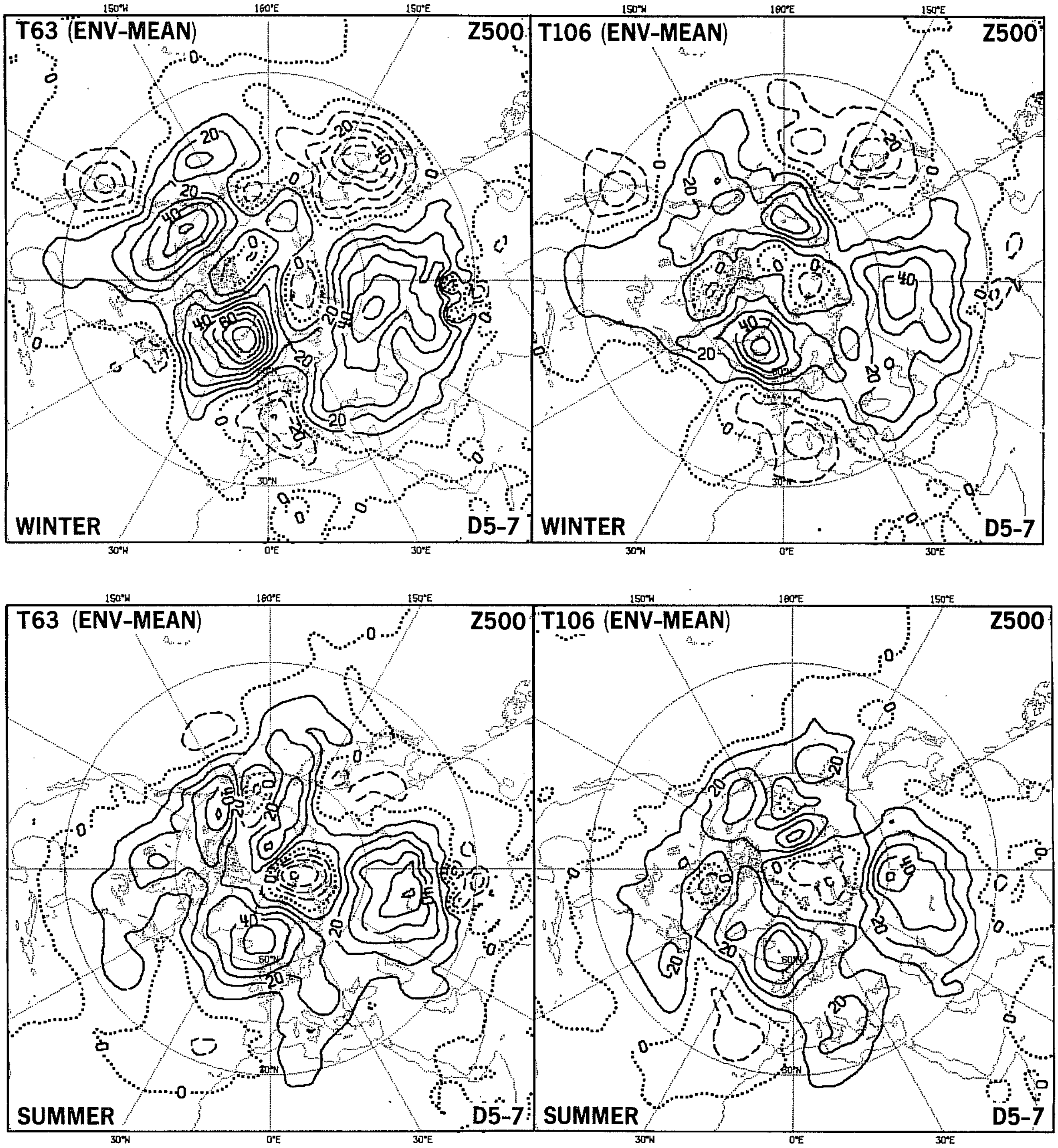


Fig. 19 As Fig. 16, but for difference corresponding to D5-7 T63 (left) and T106 (right) forecasts in winter (upper) and summer (lower).

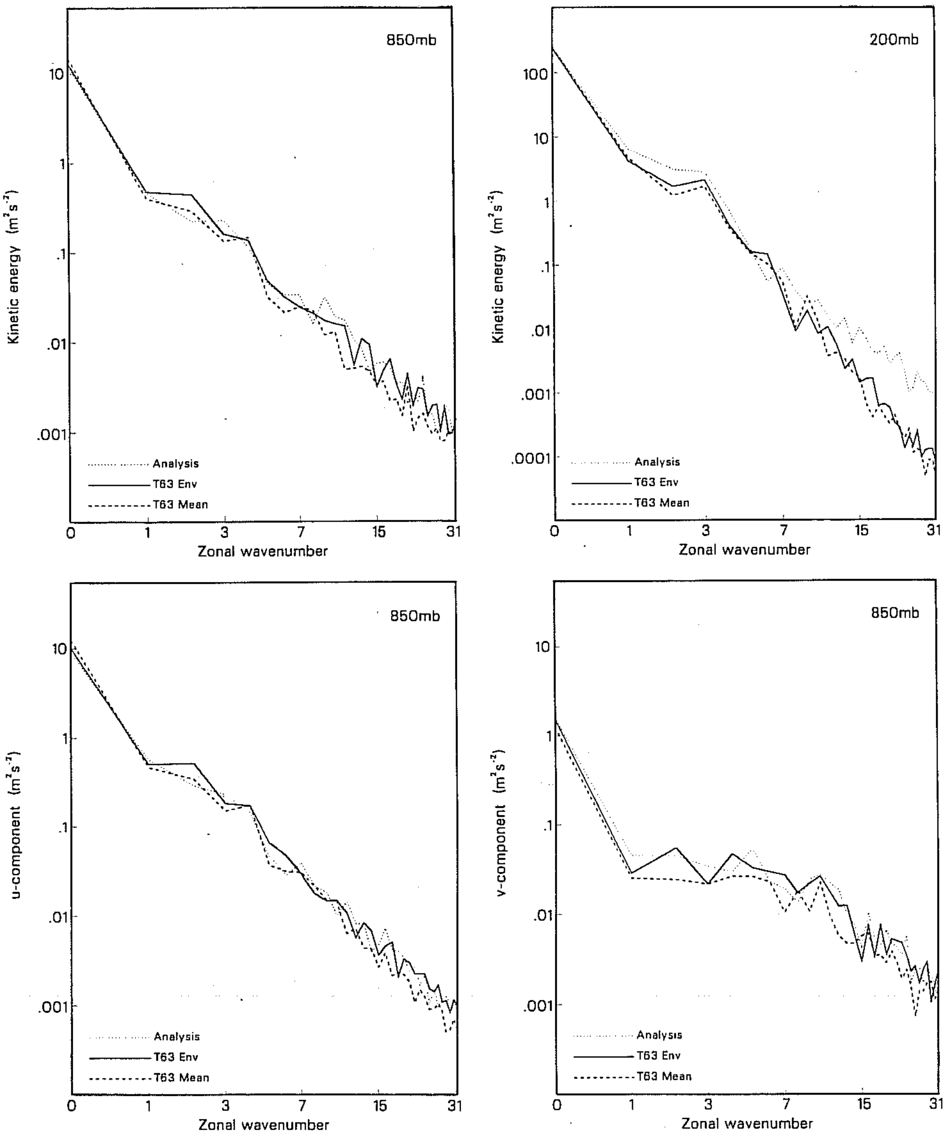
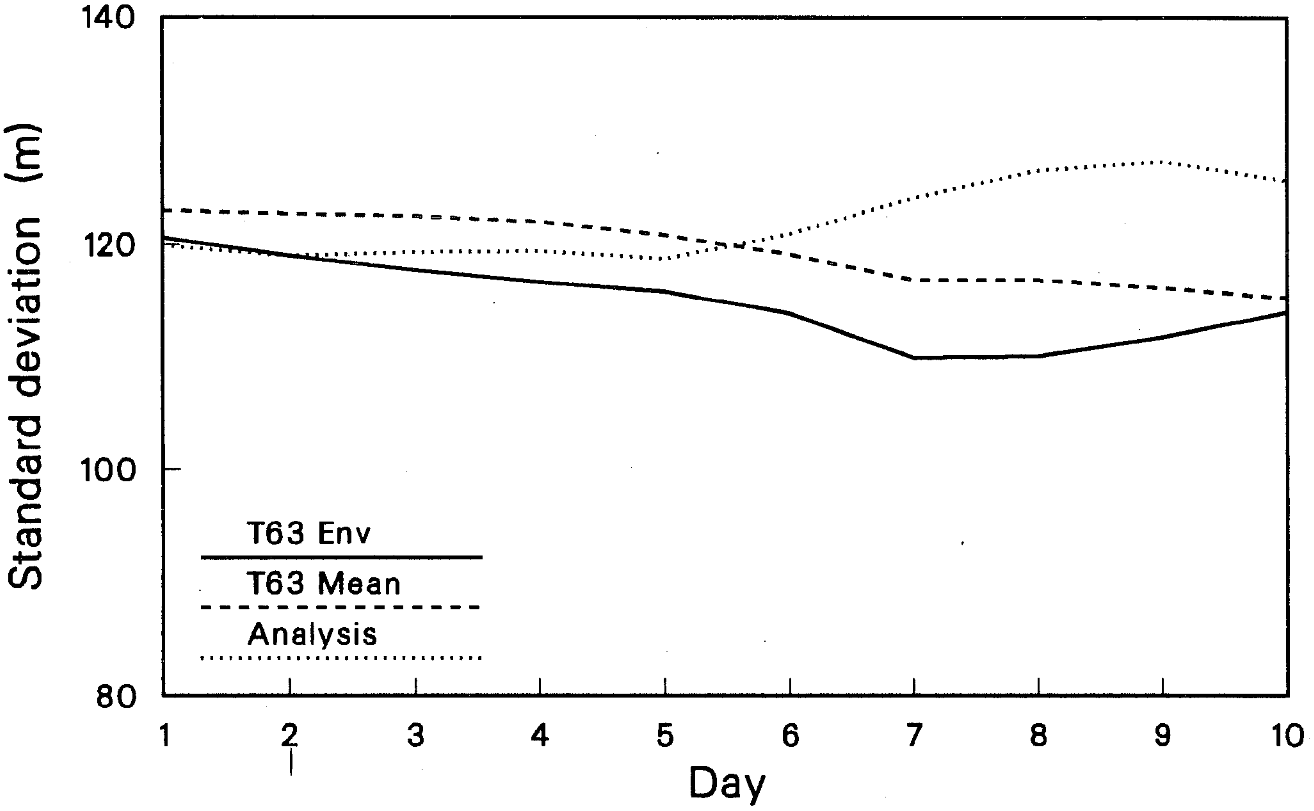


Fig. 20 Zonal spectral decompositions of the 850 mb (upper left) and 200 mb (upper right) kinetic energy densities (in m^2 s^{-2}) for the Northern Hemisphere plotted for analyses (dotted lines) and ensemble-averaged T63 forecasts, averaged also for days 8-10, using mean (dashed lines) and ($\sqrt{2}\sigma$) envelope (solid lines) orographies, for the 12 winter cases. The separate contributions of the zonal and meridional wind components to the 850 mb spectra are shown in the lower left and right panels.



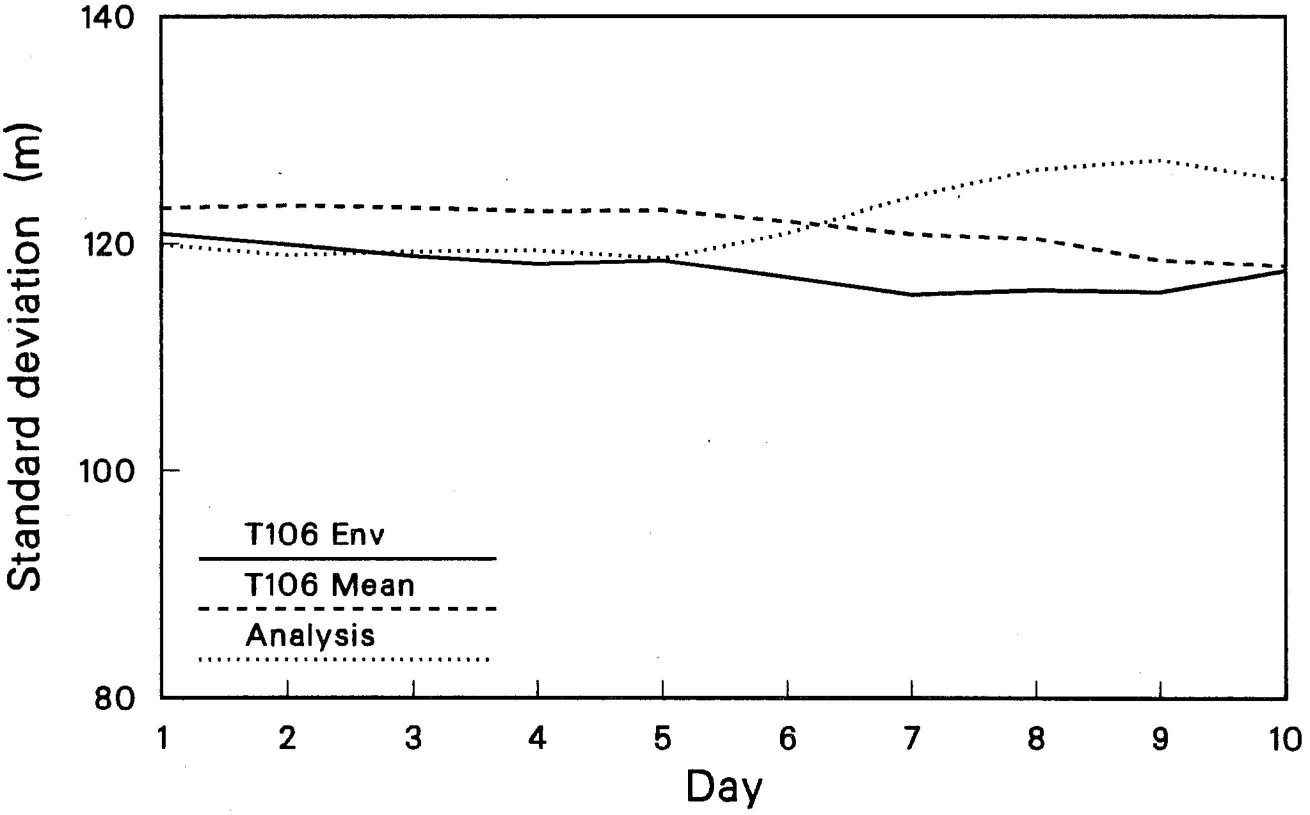


Fig. 21 Standard deviations of 500 mb height (m) from winter ensemble means computed over the extratropical Northern Hemisphere for analyses (dotted lines) and for forecasts using mean (dashed lines) and ($\sqrt{2}\sigma$) envelope (solid lines) orographies at T63 (upper) and T106 (lower) resolutions.

An early series of general-circulation experiments reported by Hills (1979) showed that enhancing orographic height, while improving the stationary-wave simulation, reduced the eddy kinetic energy associated with transient waves from a level which was already lower than observed. This prompted Wallace et al. (1983) to examine the impact of envelope orography on transient activity in a 50-day simulation. They indeed found that the transient variance of the 500 mb height field was reduced over the Northern Hemisphere, but contrary to the earlier experience it was reduced from a level which was higher than observed and became closer to reality.

For the present series series of medium-range forecasts, transient variability has been assessed by calculating the standard deviation of the individual forecast and analysis fields from their ensemble means. Results computed over the extratropical Northern Hemisphere are shown in Fig.21 for 500 mb height at each day within the 10-day range for T63 and T106 winter forecasts. The use of envelope orography here too results in a reduction in variability. Over the first half of the range this is such as to bring the forecasts closer to the analyses, particularly for T106 resolution. The situation is less clear for days 5 to 10, but it should be noted that the analysis curve is far from flat, and there is thus a question mark over the representativeness of this calculation of variance based on a sample of 12 cases.

6. SOME RESULTS FOR THE SOUTHERN HEMISPHERE AND THE TROPICS

Although most attention has been paid to investigating results for the Northern Hemisphere, some consideration has also been given to the sensitivity of forecasts for the Southern Hemisphere and the tropics.

Not surprisingly, in the Southern Hemisphere the sensitivity to the representation of orography is less at all model resolutions and seasons than found for the Northern Hemisphere. An exception is for the T21 resolution which appears anomalous in a number of respects and which seems, due to its coarseness, to misrepresent significantly the effect of the Antarctic massif. In most individual cases examined at higher resolution the differences originated near the southern Andes and Drake passage, although they did not grow to the amplitude found for the Northern Hemisphere. They were slightly larger in the Austral winter than in summer.

The relative importance of the Southern American sector for the evolution of differences shows up clearly in the evolution of ensemble-average winter differences between forecasts with mean and envelope orography. In particular, Fig.22 shows how the day-1 difference at 200 mb is concentrated in this region. Subsequently, there is an upstream propagation of a zonally-elongated difference and downstream propagation of shorter wavelength, meridionally-elongated differences. This pattern is in apparent accord with that predicted by the linear theory of Rossby-wave dispersion, and by barotropic numerical and laboratory models (e.g. Ibbetson and Phillips, 1967; Hoskins et al., 1977). Very similar results are obtained at T42 and T106 resolution, but not at T21, for which mean differences tend to develop also near Antarctica. Also of interest is the fact that, unlike the Northern Hemisphere, the short-range mean error exhibits a pattern which, except for the Andes, cannot be obviously associated with mountain ranges. This probably reflects some systematic problems with isolated individual observations, as discussed by Hollingsworth et al. (1986).

In the tropics, sensitivity to the choice of orography has been found in the lower troposphere for some objective scores (anomaly correlation of 1000 mb height, absolute correlation of 850 mb wind) but not for standard deviation or root mean square scores. The difference increases mostly in the first two days and is then more or less uniform.

To relate these objective differences to a synoptic interpretation, one example over the southern Asia region is presented where the signal from objective verification was particularly clear, and which was found by Krishnamurti et al. (1984) to be very sensitive to the use of an envelope orography. Fig.23, presents day-2 forecasts of 850 mb wind at T63 resolution for the 15 June 1984 case. Several features are slightly better simulated using the envelope, specifically the cyclonic curvature of the flow in the South China Sea, and over Burma, and a more accentuated trough south of Sri Lanka. The latter is consistent with a more substantial influence of the mountains in the southwest of India (the Western Ghats), as emphasized by Krishnamurti et al. (loc. cit.). However some features are worse with the envelope. The wind off the Somalian coast and over Southern China are too strong; this contributes to the different signal seen in the root mean square error.

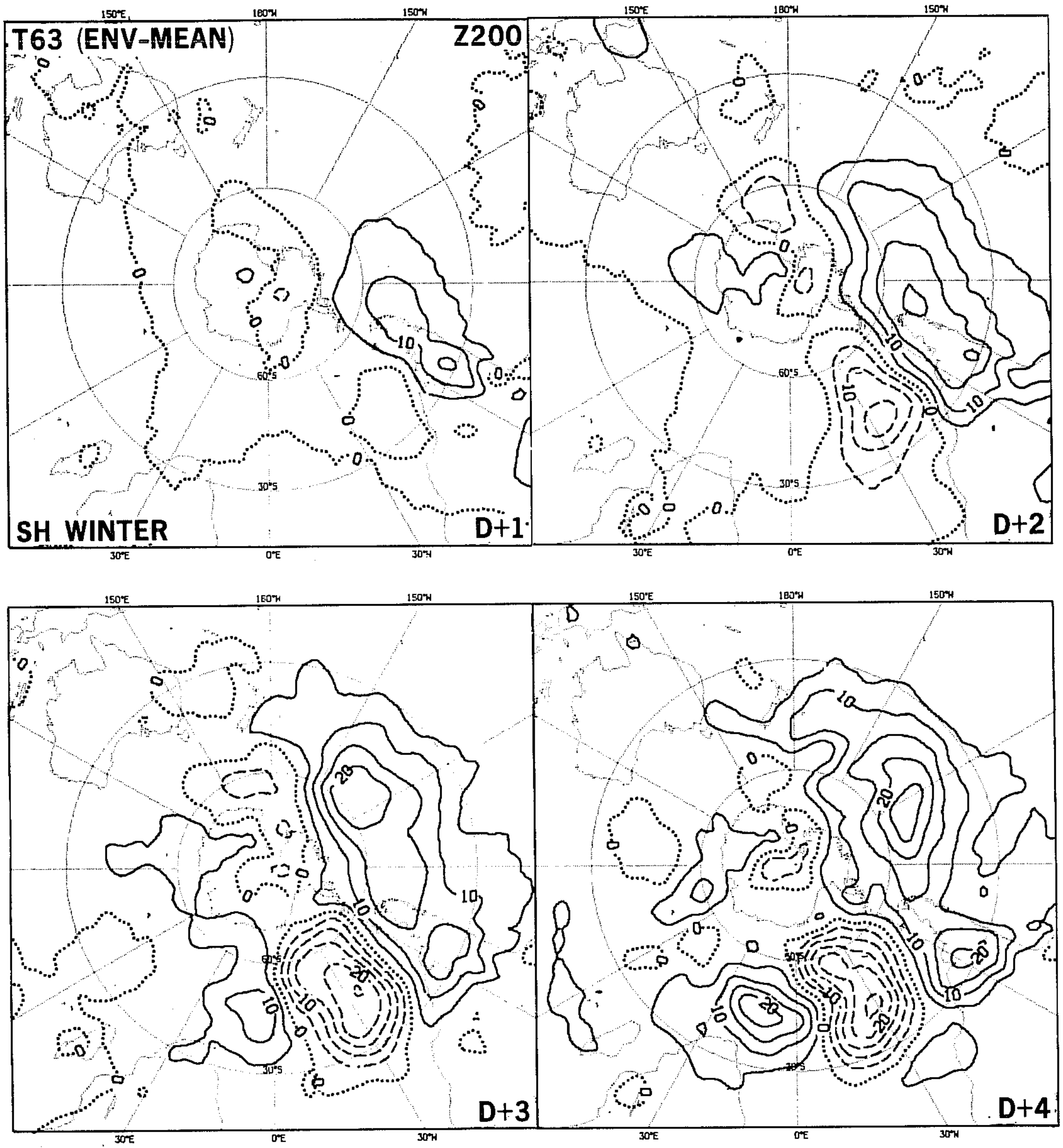


Fig. 22 Average differences between mean and envelope orography forecasts for days 1 to 4, as in Fig. 16, but for the 200 mb height field in the Southern Hemisphere (Southern Hemisphere winter cases).

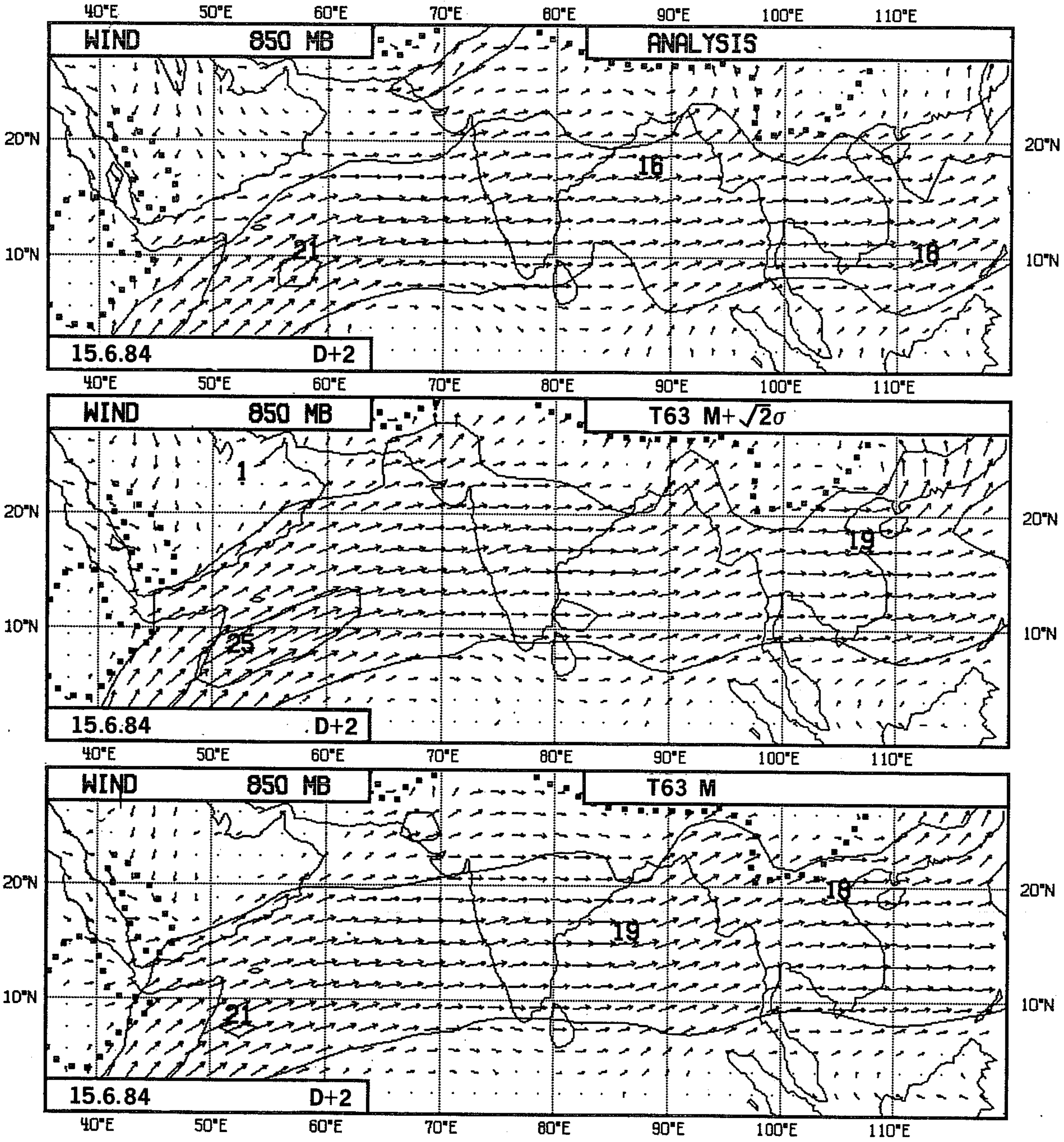


Fig. 23 Analysed 850 mb wind field for 17 June 1984 (upper) and D+2 T63 forecasts verifying on this date using envelope (middle) and mean (lower) orography.

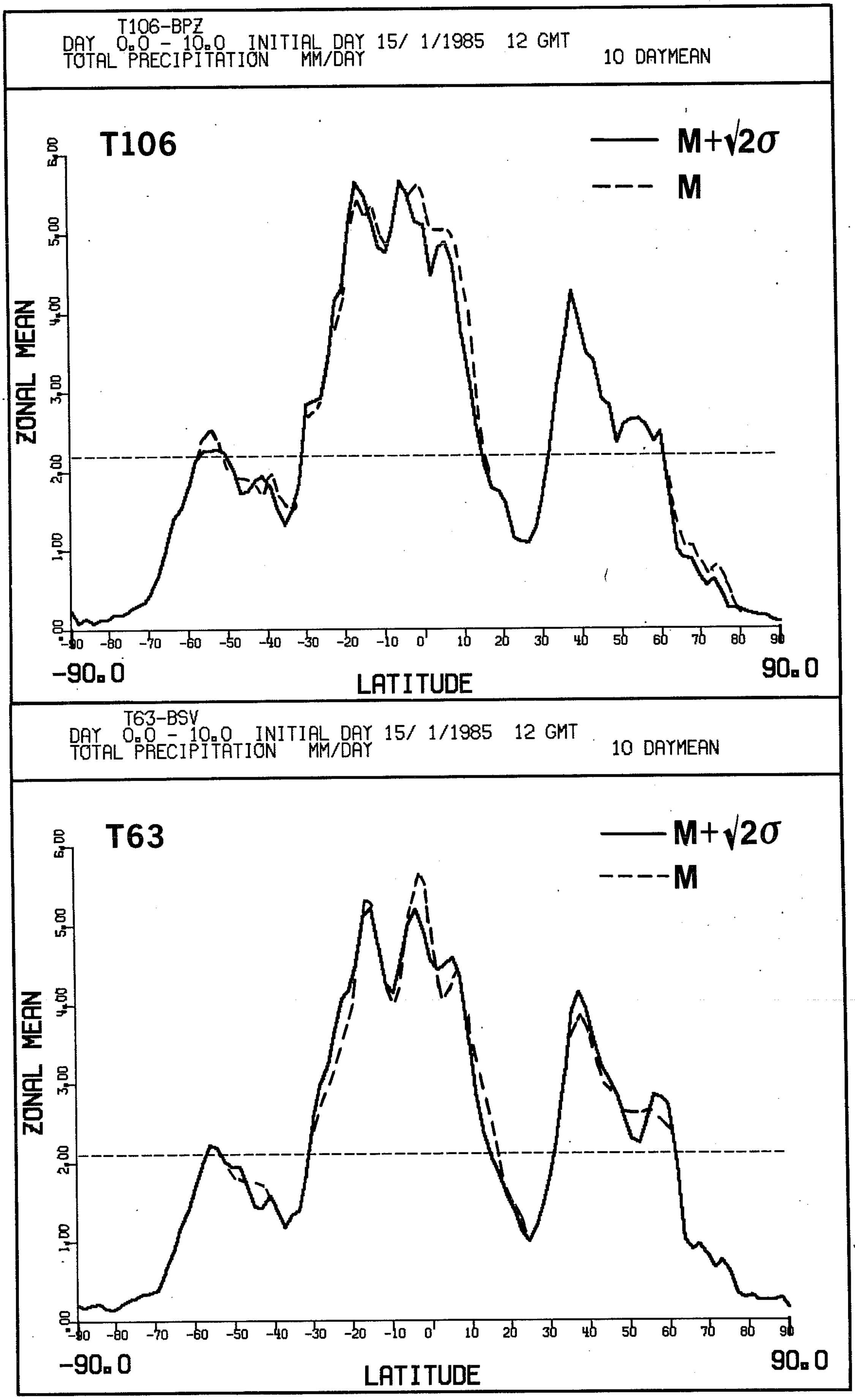


Fig. 24 10-day accumulated total precipitation, zonally averaged from T63 (lower) and T106 (upper) forecast using (√2σ) envelope (full line) and mean (dashed line) orography for the 15 January 1985 case.

It should be stressed that results for this region may be to a significant degree dependent on the physical parameterization schemes used by the model and to detailed aspects of the analysis and initialization, in particular with respect to the humidity field, as demonstrated by Krishnamurti et al. (1984).

Zonal-mean distributions of precipitation show no clearly significant increase due to use of envelope orography, as in the example shown in Fig.24. Since August 1983 the spectral model has included a modified 'horizontal' diffusion of temperature to avoid spurious warming of mountain tops and triggering of convective precipitation. This combined with the lower ($\sqrt{2}$) envelope and perhaps the use of the spectral technique probably accounts for the absence of an increase in tropical precipitation of the type reported by Tibaldi (1986). Examination of actual maps of precipitation accumulated over 10 days does, however, reveal a modest increase in the precipitation associated with mountains both in the tropics and at mid-latitudes. This is compensated by a slight reduction in the surrounding areas.

7. SUMMARY AND DISCUSSION

As part of a more general programme, a series of experiments has been performed in order to assess the impact of an envelope orography at various horizontal resolutions. The initial motivation for having an envelope was based on diagnostic studies of the initial growth of the mean errors of the model (Wallace et al., 1983) but it was also more intuitively justified by the need to represent more accurately the low level barrier effect of some mountain ranges. This point has been recently supported by simplified models (e.g. Pierrehumbert, 1984; Pierrehumbert and Wyman, 1985; Cullen et al. 1985). The results we have obtained are consistent with this supposition. In winter the envelope has been found to be generally beneficial to the quality of the forecasts at all resolutions other than T21, and the benefit is particularly clear when the flow impinges directly on mountain ranges such as the Rockies and Alps. The detrimental impact of the envelope at T21 resolution is in accord with experience elsewhere with climate simulations (Blackmon, personal communication).

In summer the situation is rather different, with the envelope having a detrimental effect at T42 and T63 resolutions, but not at T106. Synoptic analysis, and some of the experimentation using composite orographies, suggests that this may be explained by the more northerly position of the (Northern Hemisphere) jet in summer. This jet interacts with mountains which appear no longer primarily as a barrier, but more as isolated peaks (as in the case of the islands west of Greenland). At T63 and T42 resolution the envelope tends to create an artificial barrier. T106 shows less of a problem since it allows a better separation of localized features and minimizes the spreading of narrow ranges. Some problems are also seen in all seasons in connection with the envelope representation of the Asian mountains, not only the Tibetan plateau but also the other mountain ranges to the north and north-east.

In all cases the impact of the envelope has been found to cause local modifications which tend to propagate and amplify (principally on synoptic scales) following the upper level flows. A large part of the hemisphere can be influenced in 7 to 10 days. The largest differences are found to take their origin and develop in regions of intense activity (strong gradients, deep lows, etc.). This <u>local</u> amplification and spreading is in part <u>immediately</u> perceived diagnostically as a modification to the low zonal wavenumber components of the flow, and it is evident that care has to be exercised in the interpretation of results of spectral analysis.

Furthermore, the short range differences tend to be similar at all resolutions (including T21) indicating that the effect of the envelope at higher resolution (T63 and T106) does not come only from the shortest scales. This result is also consistent with the hypothesis that the important feature is the enhancement of the local height of the barrier presented to the flow. However, our results (particularly in summer) also show the limitation of such an approach, especially at lower resolutions, since it is not desirable to create a barrier effect for all types of mountains (for example isolated mountains). Moreover, this effect should ideally depend on the direction and static stability of the incident flow.

It seems, therefore, desirable that more sophisticated approaches be investigated to simulate this dynamical effect, in particular for models with rather low resolution. Such a strategy is not an alternative, but rather a complement to the parameterizations of gravity wave drag and of subgrid stress effects due to mountains since they clearly correspond to different physical processes. However, since all three processes act to reduce the overall westerly flow in middle latitudes, care must be taken during model development to achieve the correct balance between these mechanisms. There is an evident danger in tuning one representation to compensate for the deficiencies (or absence) of another.

Finally, in the rather general context of the strategy to be followed when testing model changes, it is appropriate to stress the merits of the experimental approach adopted for this study, namely the use of a substantial number of cases selected from as wide a range of different synoptic situations as possible. Had the programme of forecasts been run using a sample of just 12 cases drawn from one year only, quantitative conclusions concerning the impact of the envelope would have been modified. More significantly, some of the conclusions drawn from previous studies based on a limited spell within one particular season have not been found to apply over a broader selection of cases. The range of cases studied also helped understanding of the mechanics involved by providing many different examples of the response of the flow to enhanced orography. The approach adopted here is, however much, less easy to follow if the model change to be selected requires a spell of preliminary data assimilation for reliable assessment.

Acknowledgement

We are indebted to J.M. Hoyer for the help he gave us in the experimental phase, and to H. Pümpel and H. Böttger for many helpful remarks and discussions in the synoptic assessment of the results.

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